Measurement of the Cross Section for Prompt Isolated Diphoton Production in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV

Costas Vellidis

FNAL

Prompt γγ production in hadron colliders

- **Prompt photons** = emitted from quarks in hard scattering processes, as opposed to coming from neutral hadron decays (reducible background in cross section measurements)

- The cleanest probe of QCD — elementary particles, can be measured with **high precision** in modern calorimeters

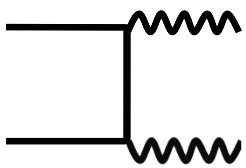
- Probe for searching **new phenomena** — γγ is signature of possible heavy resonance decays

Prompt γγ production in hadron colliders

- **Measurements** of cross sections are needed to test perturbative (and non-perturbative) QCD predictions in order to improve our understanding of the production mechanism
- Improvements of searches for new resonances require a good understanding of the QCD **production mechanism** (irreducible background in resonance searches)
- **Tevatron** and **LHC**: ideal places to conduct γγ measurements — well performing colliders, high precision detectors

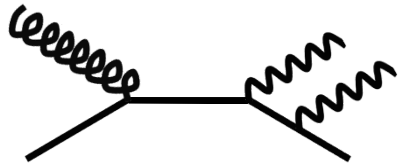
Prompt γγ production in hadron colliders

Hard QCD ("direct" γγ production):



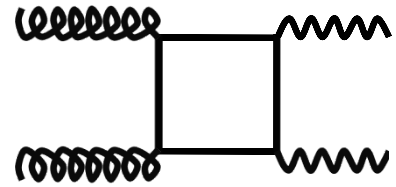
$q\bar{q} \to \gamma\gamma$

Born: Dominant
at the Tevatron



$gq \to \gamma\gamma q$

Brems: Suppressed by
the isolation requirement



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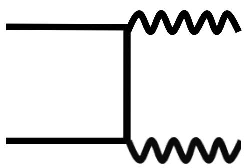

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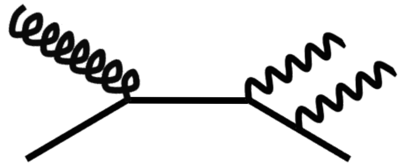

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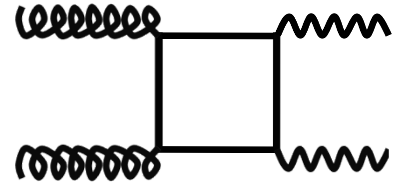

$gg \to \gamma\gamma$

"Box": Dominant
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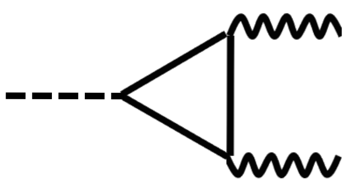
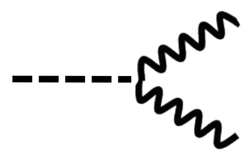
Possible heavy resonance decays:



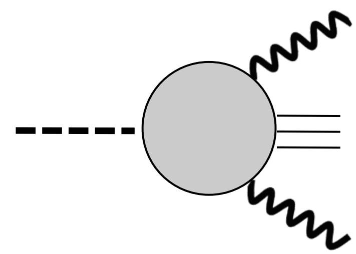
$H \to \gamma\gamma$

Low-mass Higgs boson
(most sensitive channel at LHC for m_H<125 GeV/c^2)



$G^* \to \gamma\gamma$

Extra dimensions



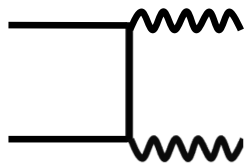
$W \to \gamma\gamma + X$

SUSY

Prompt γγ production in hadron colliders

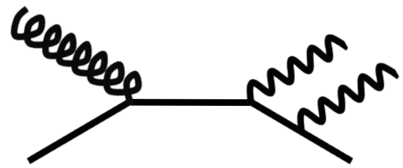
Hard QCD ("direct" γγ production):

Better control on these processes
[σ ~ O(10 pb) at the Tevatron]



$$q\bar{q} \rightarrow \gamma\gamma$$

Born: Dominant
at the Tevatron



$$gq \rightarrow \gamma\gamma q$$

Brems: Suppressed by
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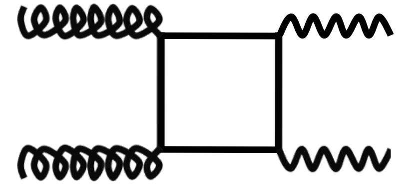
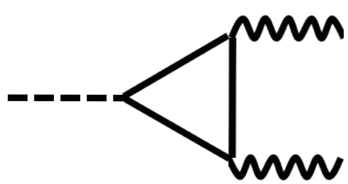


$$gg \rightarrow \gamma\gamma$$

"Box": Dominant
at the LHC

Possible heavy resonance decays:

➔ More sensitive searches for such processes
[σ × BR ~ O(1 fb) at the Tevatron]



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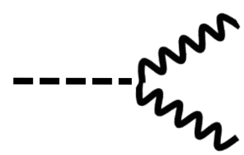

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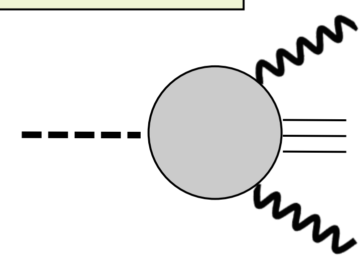
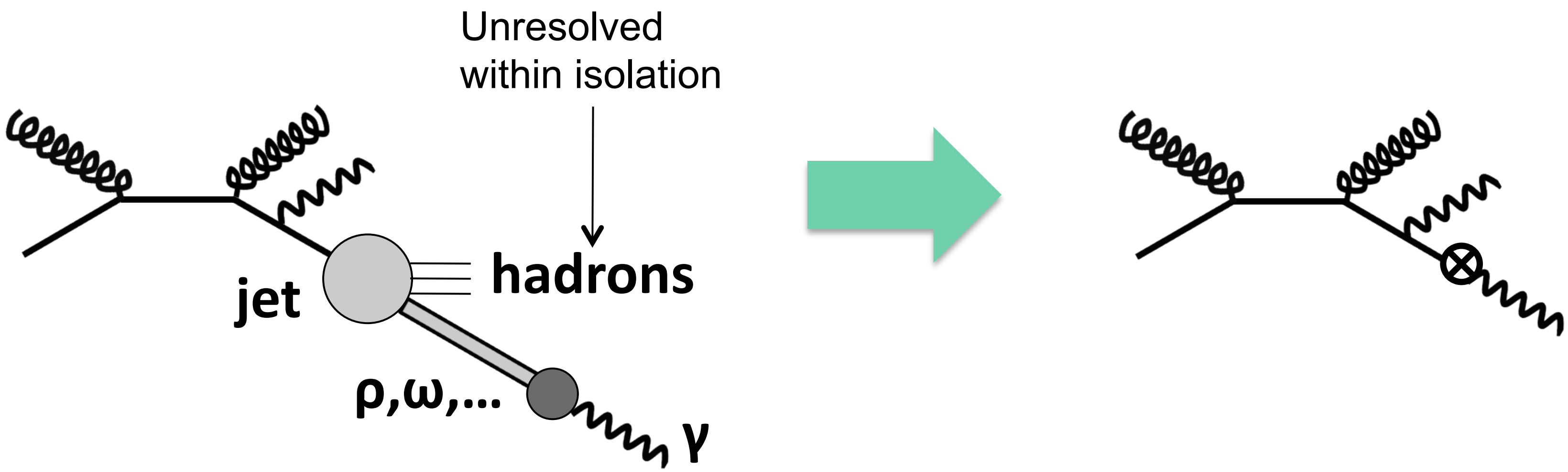


$$W \rightarrow \gamma\gamma + X$$

SUSY

Aspects of the theory: Fragmentation



- The pQCD cross section is divergent when q and γ are collinear ➔ Non-perturbative feature of the theory, handled with phenomenological “fragmentation functions” derived e.g. from the VMD model [L. Bourhis *et al*., Eur. Phys. J. C **2**, 529 (1998)].

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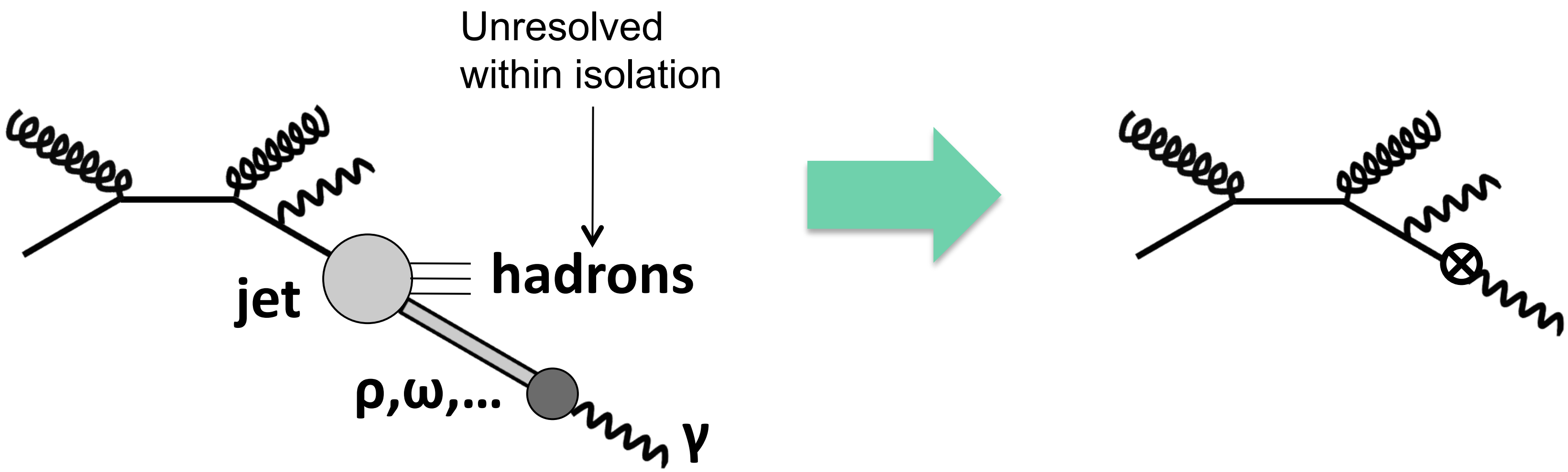

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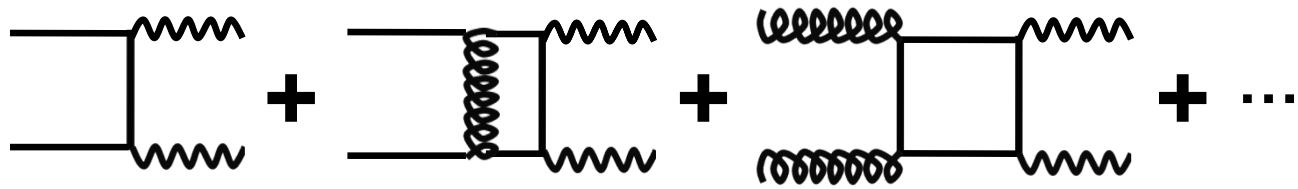
- Fragmentation contributions can be suppressed by
  - $P_T(\gamma\gamma) < M(\gamma\gamma)$
  - experimental photon isolation requirements $\longrightarrow$ $$E_T^{iso} = \sum_{\substack{\text{partons or hadrons}\\ \text{within } R<0.4}} E_T - E_{T\gamma}$$

Aspects of the theory: Resummation

The cross section for



contains singular terms at $P_{\mathrm{T}}(\gamma\gamma) \to 0$ and M(γγ) ≠ 0 of the form

$$\frac{\alpha_s^n}{P_{\mathrm{T}}^2(\gamma\gamma)} \ln^m \frac{M^2(\gamma\gamma)}{P_{\mathrm{T}}^2(\gamma\gamma)} \quad \text{or} \quad -\alpha_s^n \delta\left(\vec{P}_{\mathrm{T}}(\gamma\gamma)\right) \qquad n = 1,\ldots\infty \qquad m = 0,\ldots,2n-1$$

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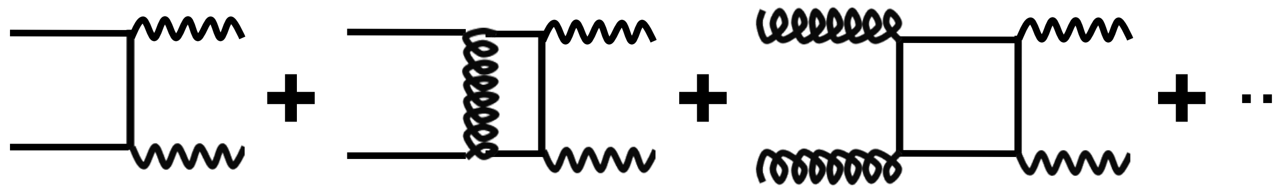

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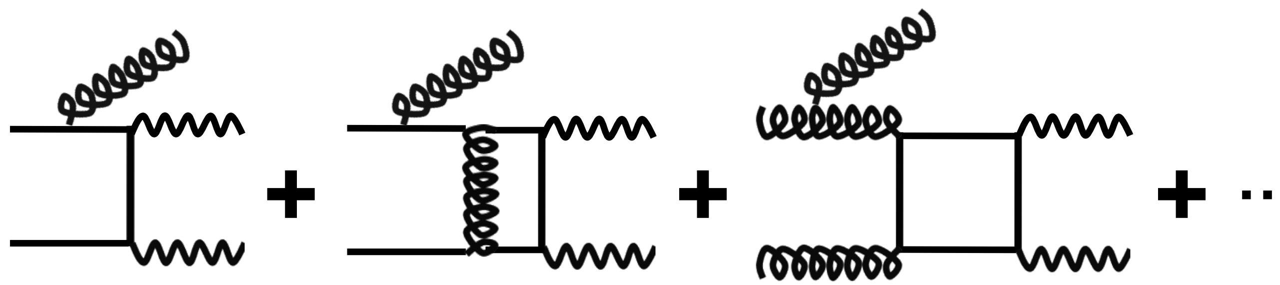
Need to add
soft gluon emission:



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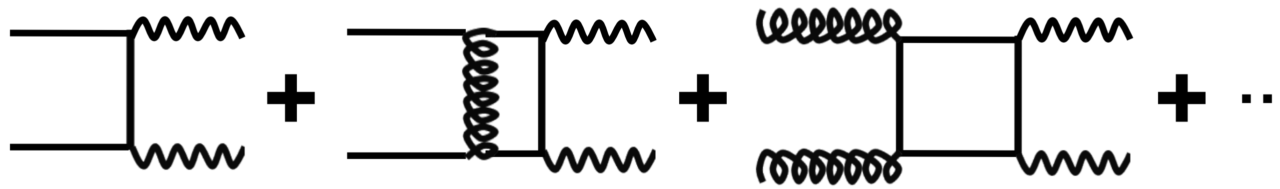

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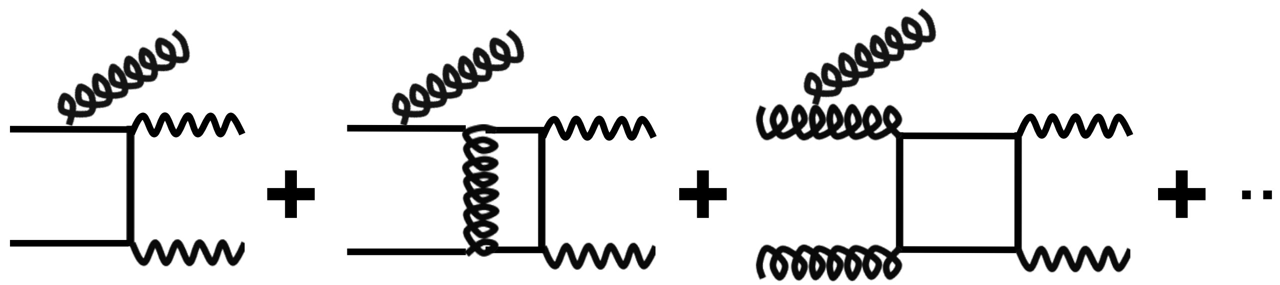


- Two ways of doing this:
  - Approach the $P_{\mathrm{T}}(\gamma\gamma) \to 0$ limit with an analytically calculated cross section derived from the sum of the singular terms for all n and m = 1,2,3 (next-to-next-to-leading log accuracy, NNLL), which is then smoothly matched to the perturbative cross section at high $P_{\mathrm{T}}(\gamma\gamma)$
  - Use parton showering to add gluon radiation in a Monte Carlo simulation framework which effectively resums the cross section for all n and m = 1 (leading-log accuracy, LL)

Theoretical predictions

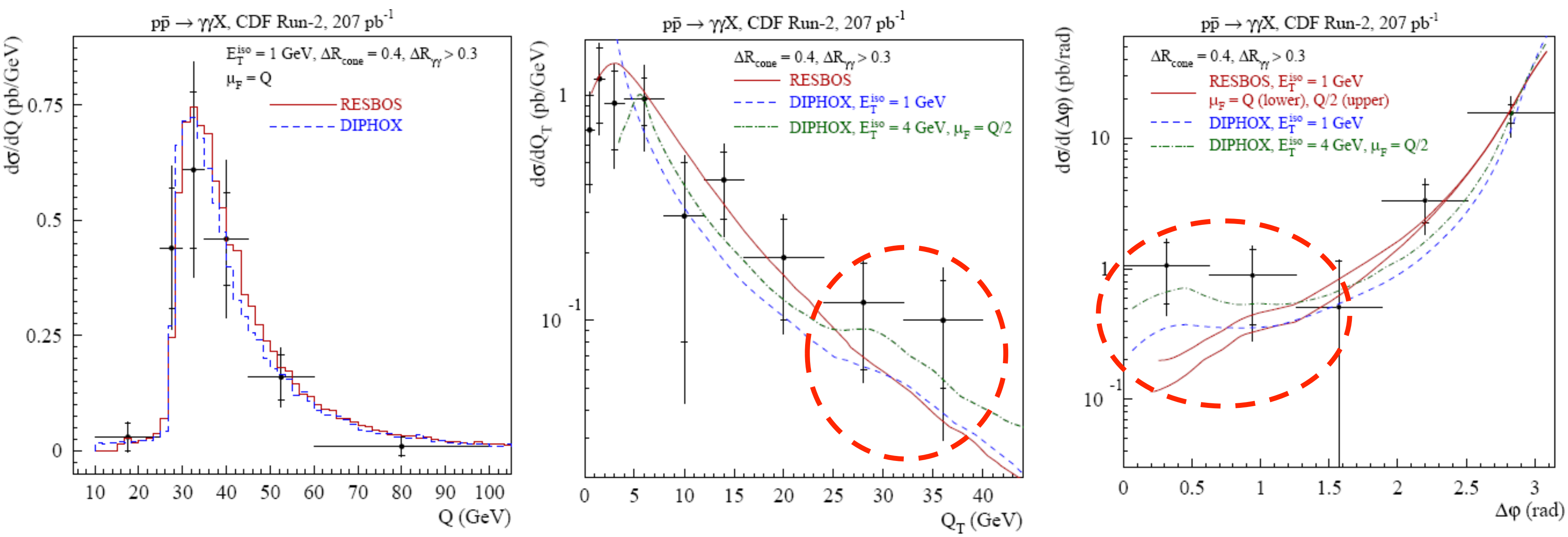
- **DIPHOX**: Fixed-order NLO calculation including non-perturbative fragmentation
  [T. Binoth *et al*., Phys. Rev. D **63**,114016 (2001)]

- **RESBOS**: Low-P_T analytically resummed calculation matched to high-P_T NLO
  [T. Balazs *et al*., Phys. Rev. D **76**, 013008 (2007)]

- **PYTHIA** LO parton-shower calculation
  [T.Sjöstrand *et al*., Comp. Phys. Comm. **135**, 238 (2001)]

Previously published measurements

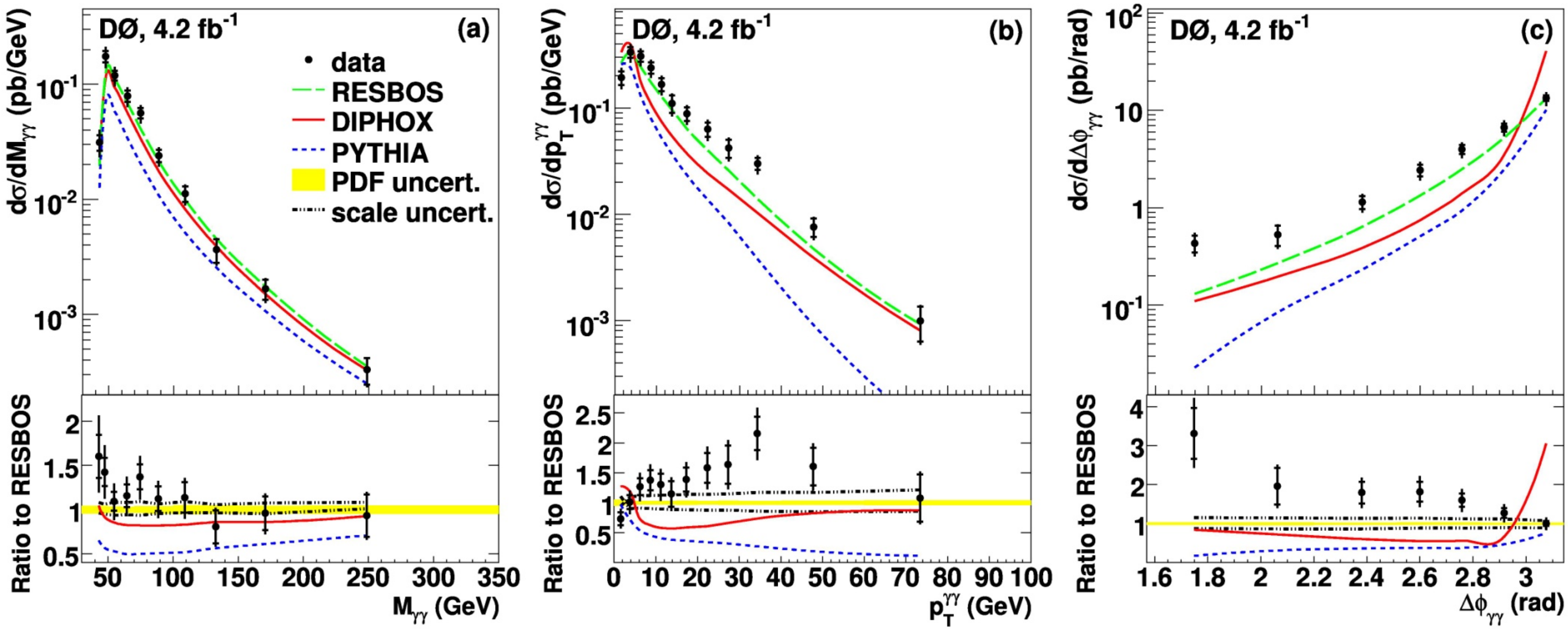
- CDF publication in Run II with 207 pb^{-1}. *PRL 95, 022003 (2005)* *PRD 76, 013009 (2007)*
- Event selection: $p_{T1(2)}$>14(13) GeV, $|\eta_{1,2}|$<0.9, $\Delta R(\gamma,\gamma)$>0.3, E_T^{iso}<1 GeV.



- $P_T(\gamma\gamma)$>25 GeV region in data dominated by events with $P_T(\gamma\gamma)$>$M(\gamma\gamma)$ and $\Delta\phi(\gamma,\gamma)<\pi/2$ ➔ potentially large fragmentation contributions.

Previously published measurements

- D0 publication in Run II with 4.2 fb^{-1} *PLB 690, 108 (2010)*
- $p_{T1(2)}$>21(20) GeV/c, $|\eta_{1,2}|<1$, $\Delta R(\gamma,\gamma)>0.4$, $(E_{tot}^{R=0.4} - E_{em}^{R=0.2})/ E_{em}^{R=0.2} < 0.1$, $P_T(\gamma\gamma)<M(\gamma\gamma)$



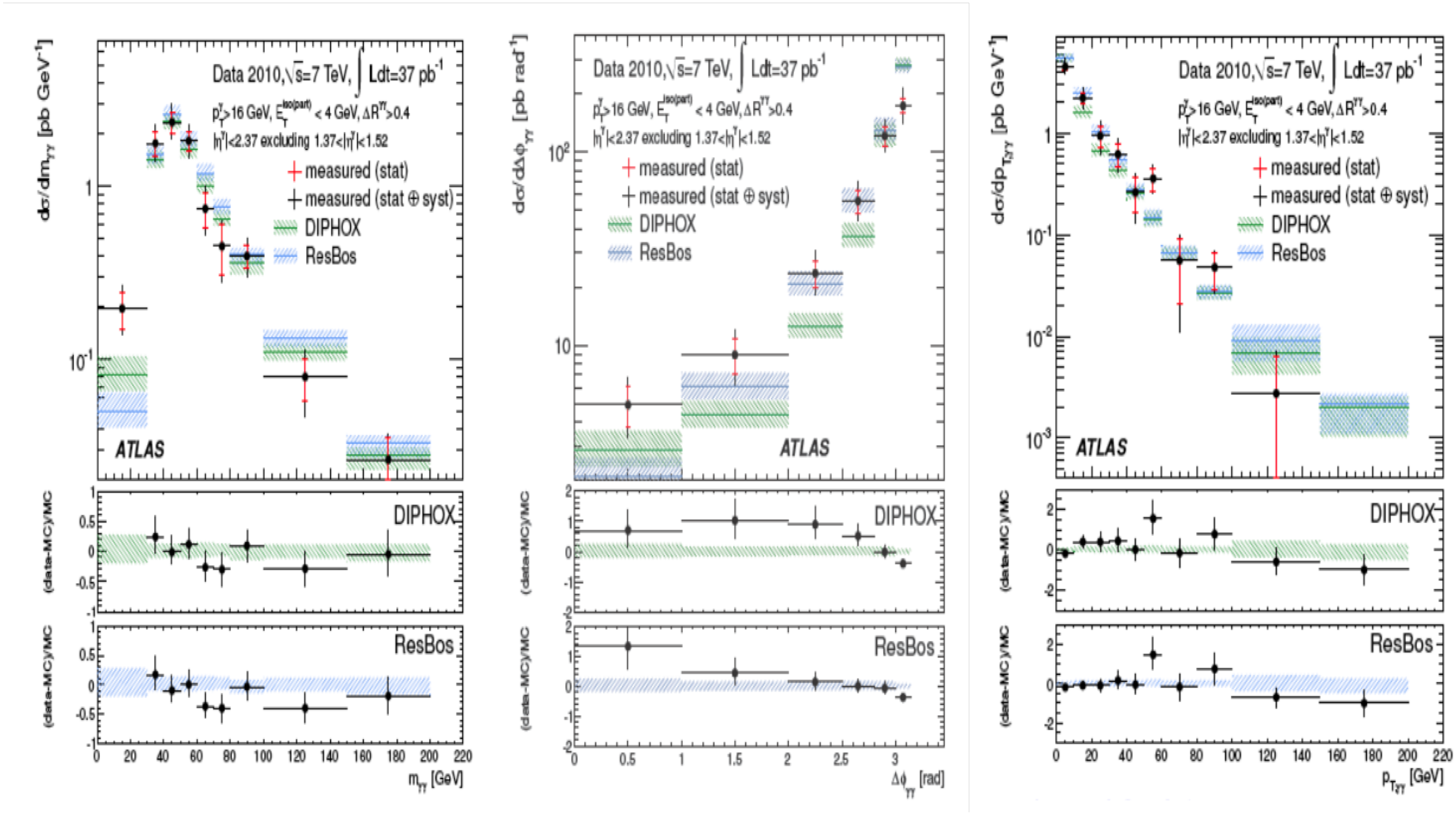
- Good agreement between data and RESBOS for $M_{\gamma\gamma}$>50 GeV/c^2
- Need for a resummed calculation
- Data spectrum harder than predicted
- Observable nearly insensitive to experimental effects
- Supports conclusion from P_T ($\gamma\gamma$) measurement

(*) Overall normalization uncertainty (7.3%) not included in data error bars.

Here the PYTHIA prediction uses only matrix element based production of photon pairs

Recent measurements at the LHC

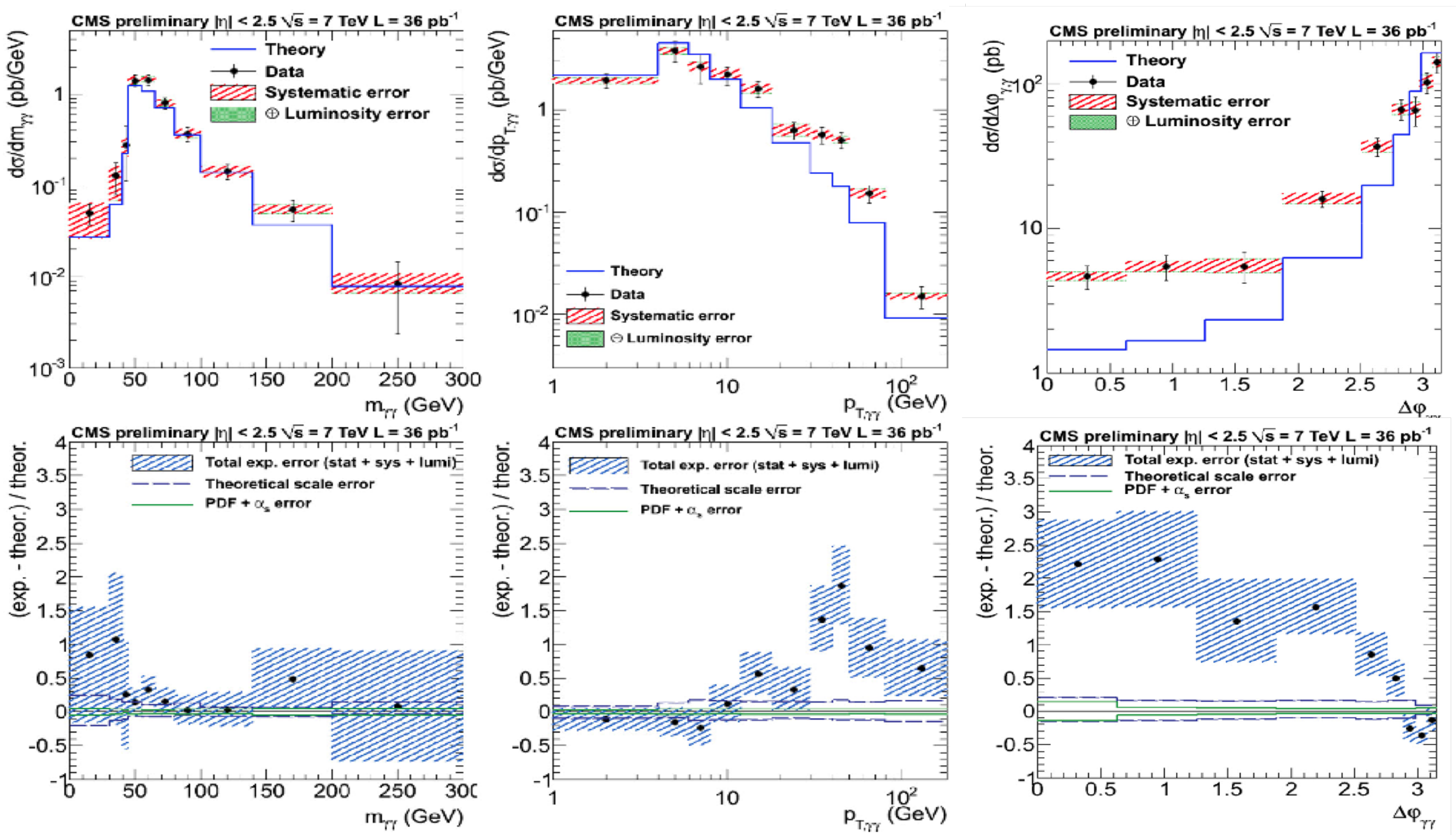
- Preliminary ATLAS results using 37 pb^{-1}, CERN-PH-EP-2011-08, EPS-HEP2011
- Event selection: $p_{T1(2)}$>16 GeV, $|\eta_{1,2}|$<2.37, $\Delta R(\gamma,\gamma)$>0.4, E_t^{iso}<3 GeV.



- Confirm the discrepancies observed at the Tevatron

Recent measurements at the LHC

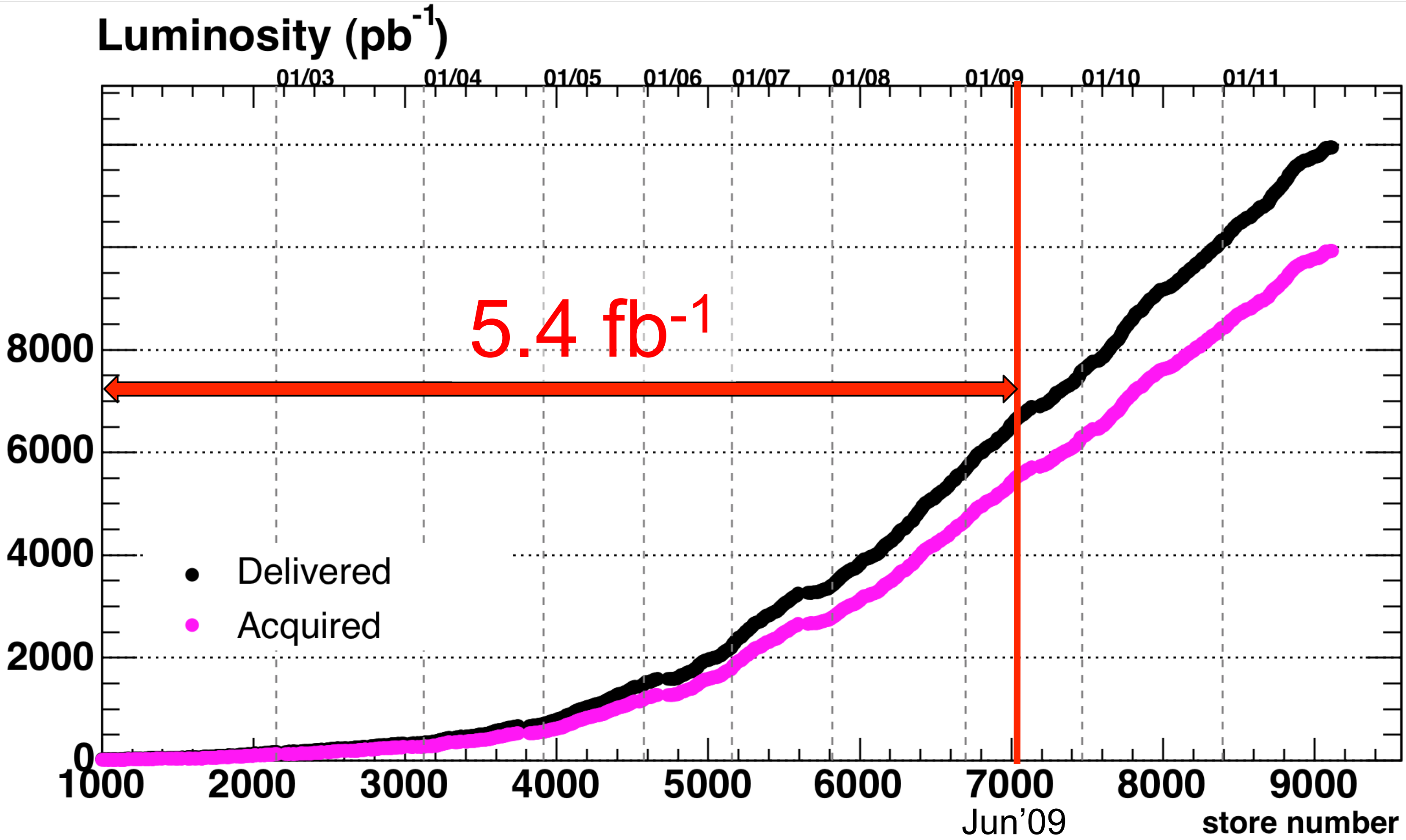
- Preliminary CMS results using 36 pb^{-1}, CMS QCD 10-035, EPS-HEP2011, APS-DPF2011
- Event selection: $p_{T1(2)}$>23(20) GeV, $|\eta_{1,2}|$<2.5, $\Delta R(\gamma,\gamma)$>0.45



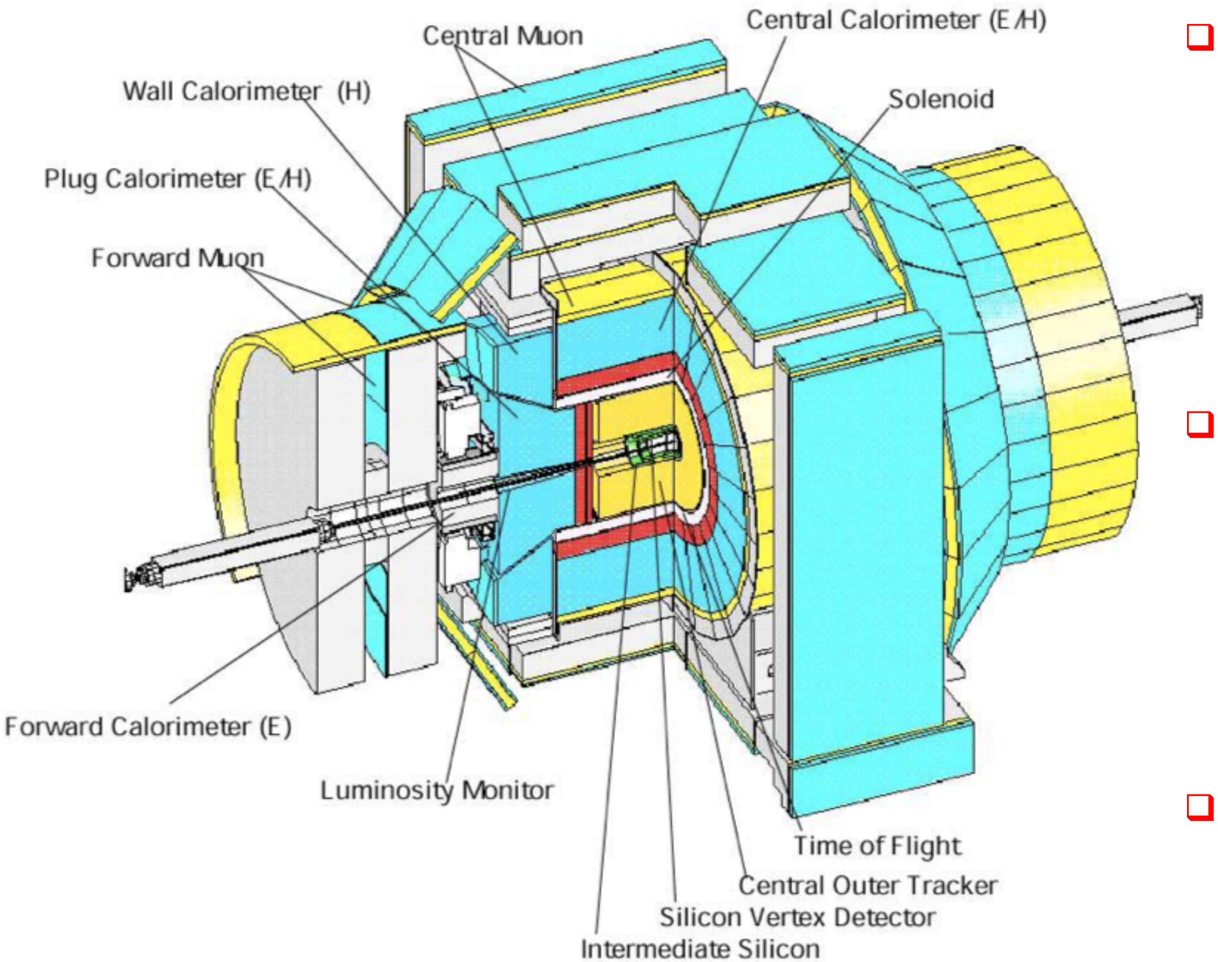
- Similar conclusions, large data – DIPHOX discrepancy for $\Delta\phi(\gamma,\gamma)<\pi/2$

Data set

Many thanks to the Accelerator Division!



CDF detector overview



- **Tracking:**
  - → Drift chamber, $|\eta|<1$
  - → Silicon microstrip tracker, $|\eta|<2$ allows also for precise vertex reconstruction
- **Calorimeter:**
  - → Split in EM (scintillator – lead) and HAD (scintillator – iron) sampling devices, $|\eta|<1.1$ (central), $1.1<|\eta|<3.6$ (plug)
- **Muon system:**
  - → Drift chambers outside calorimeter, $|\eta|<1.5$

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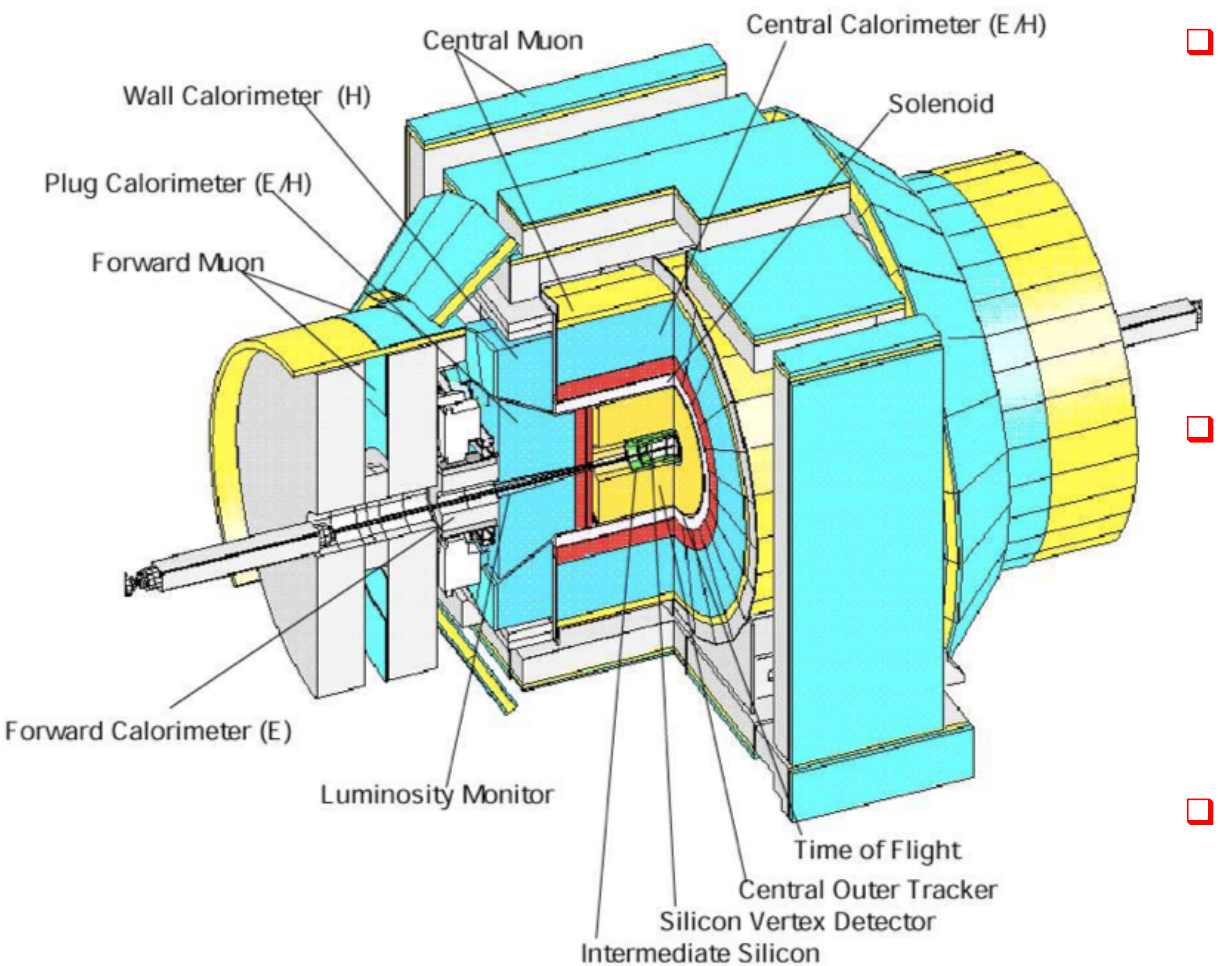

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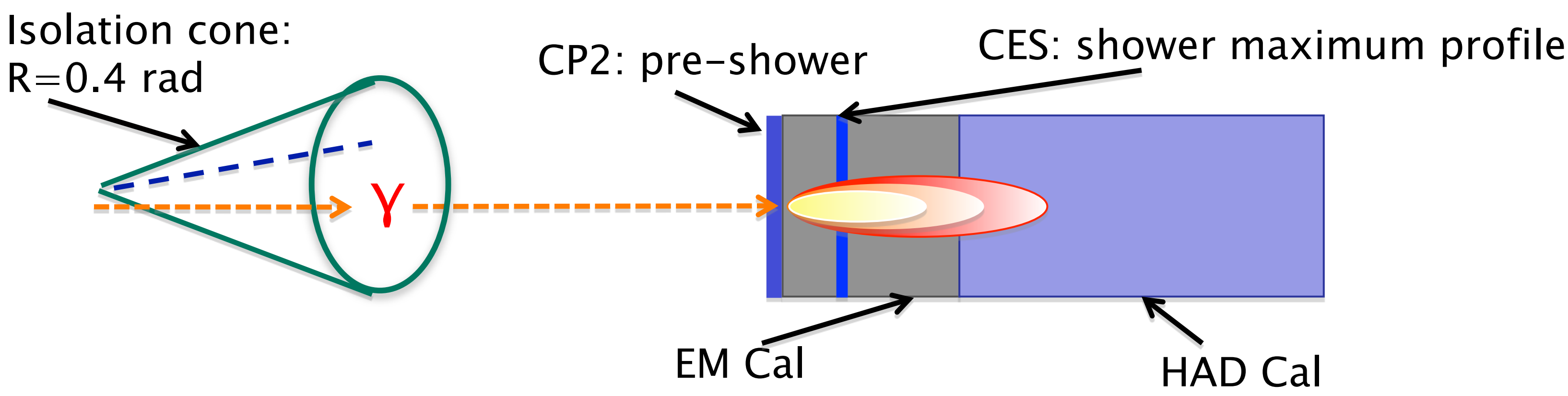
- **Muon system:**
  - → Drift chambers outside calorimeter, $|\eta|<1.5$
- **Central electromagnetic calorimeter ($|\eta|<1.1$):**
  - → Tower segmentation: $\Delta\eta \times \Delta\phi \cong 0.1 \times 15^o$
  - → Resolution: $\sigma(E)/E = 13.5\%/\sqrt{E(\mathrm{GeV})} \oplus 1.5\%$
  - → Proportional chambers (CES) at 6 rad. lengths depth (shower max) give location and 2D profile of the EM showers (position resolution ~2 mm for 50 GeV γ)

Photon identification and event selection



- Used dedicated diphoton triggers with optimized efficiency
- Photons were selected offline from EM clusters, reconstructed within a cone of radius R=0.4 in the η–ϕ plane, and requiring:
  - Fiducial to the central calorimeter: $|\eta|<1.1$
  - $E_T \geq 17$ GeV (1^{st} γ in the event), 15 GeV (2^{nd} γ)
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV
  - Low HAD fraction: $E_{HAD}/E_{EM} \leq 0.055 + 0.00045\times E_{tot}/\text{GeV}$
  - At most one track in cluster with $p_T^{trk} \leq 1$ GeV/c $+ 0.005\times E_T^{\gamma}$/c
  - Shower profile consistent with predefined patterns: $\chi^2_{CES} \leq 20$
  - Only one high energy CES cluster: E_T of 2^{nd} CES cluster ≤ 2.4 GeV $+ 0.01\times E_T$

Avoids divergence in fixed-order calculations

Imply that $\Delta R(\gamma,\gamma) \geq 0.4$

Background subtraction

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

Jets misidentified as photons: dijet and γ+jet

➔ Fluctuations in jet fragmentation to leading π^0 or η^0 meson ($\pi^0,\eta^0 \rightarrow \gamma\gamma$)

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

Background subtraction

NEW technique!

Jets misidentified as photons: dijet and γ+jet

- ➔ Fluctuations in jet fragmentation to leading π^0 or η^0 meson ($\pi^0,\eta^0 \rightarrow \gamma\gamma$)
- ➔ Normalization and shape estimated from MC using **track isolation**: $I_{trk} = \sum_{tracks\ in\ R<0.4}^{|z_{vtx}-z_{trk}|<5cm} p_T^{trk}$
- ➔ Sensitive only to underlying event and jet fragmentation (for fake γ), immune to multiple interactions (due to z-cut) and calorimeter leakage
- ➔ Good resolution in low-E_T region, where background is most important
- ➔ Uses charged particles only

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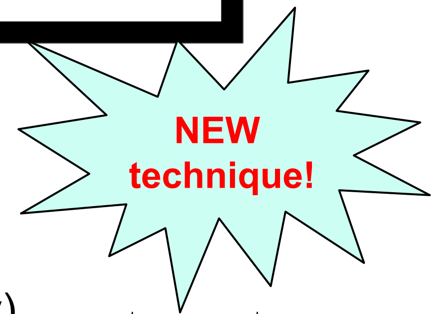

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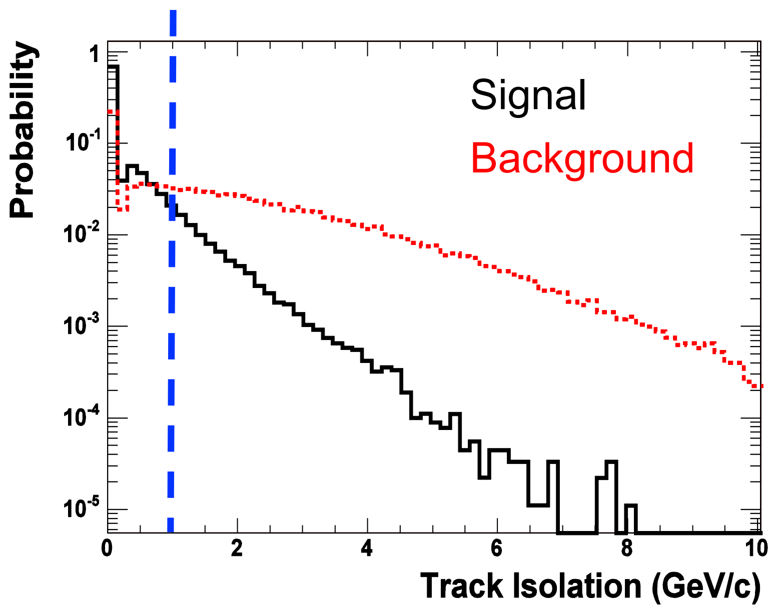
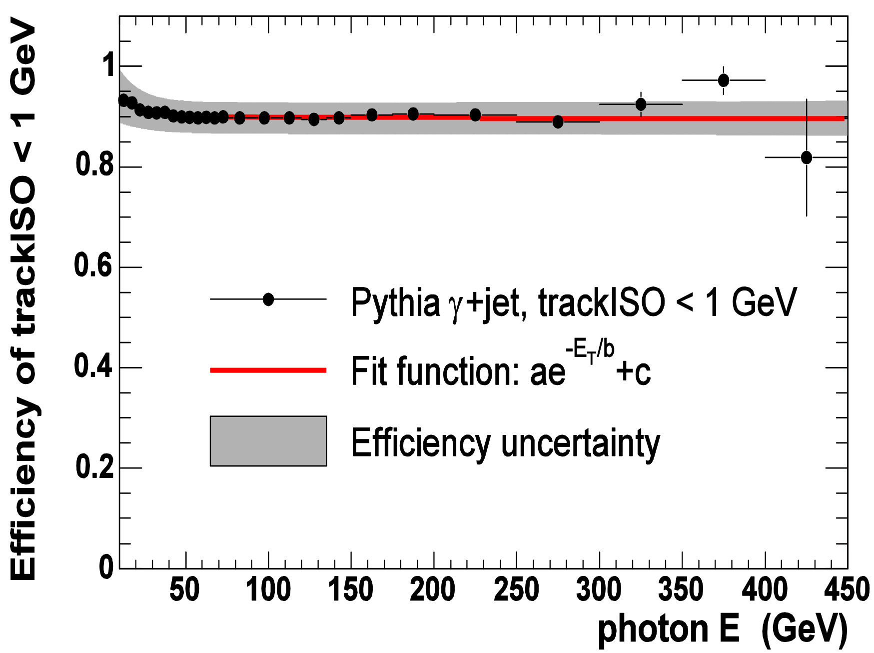
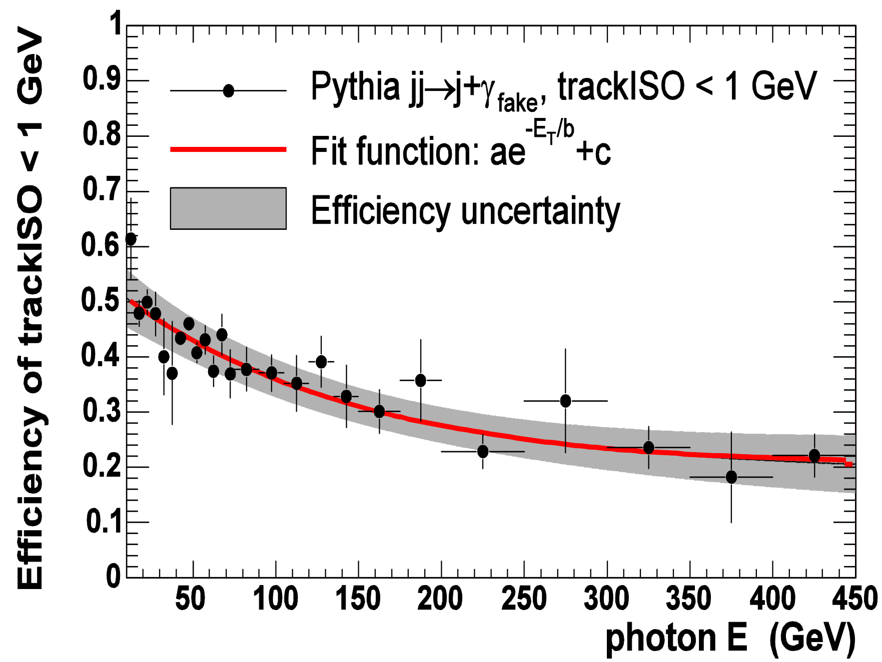
Substantially different shape of signal and background I_{trk} distributions can be used to characterize true and fake γ



Signal-background discrimination using the track isolation





For a single γ, a weight can be defined to characterize it as signal or background:

$$\boxed{w = \frac{\varepsilon - \varepsilon_b}{\varepsilon_s - \varepsilon_b}}$$

➔ ε = 1 (0) if I_{trk} < (≥) 1 GeV/c

➔ ε_s = signal efficiency for I_{trk} < 1 GeV/c

➔ ε_b = background efficiency for I_{trk} < 1 GeV/c

Both modeled by $ae^{-E_T/b} + c$

Background subtraction: 4×4 matrix method

- Use the track isolation cut for each photon to compute a per-event weight under the different hypotheses (γγ, γ+jet and dijet):

$$\begin{pmatrix} w_{jj} \\ w_{j\gamma} \\ w_{\gamma j} \\ w_{\gamma\gamma} \end{pmatrix} = E^{-1} \times \begin{pmatrix} w_{ff} \\ w_{fp} \\ w_{pf} \\ w_{pp} \end{pmatrix} \begin{array}{l} \text{Both photons fail} \\ \text{Leading fail, trailing passes} \\ \text{Leading passes, trailing fails} \\ \text{Both photons pass} \end{array}$$

$$E = \begin{pmatrix} (1-\epsilon_{j1})(1-\epsilon_{j2}) & (1-\epsilon_{j1})(1-\epsilon_{\gamma 2}) & (1-\epsilon_{\gamma 1})(1-\epsilon_{j2}) & (1-\epsilon_{\gamma 1})(1-\epsilon_{\gamma 2}) \\ (1-\epsilon_{j1})\epsilon_{j2} & (1-\epsilon_{j1})\epsilon_{\gamma 2} & (1-\epsilon_{\gamma 1})\epsilon_{j2} & (1-\epsilon_{\gamma 1})\epsilon_{\gamma 2} \\ \epsilon_{j1}(1-\epsilon_{j2}) & \epsilon_{j1}(1-\epsilon_{\gamma 2}) & \epsilon_{\gamma 1}(1-\epsilon_{j2}) & \epsilon_{\gamma 1}(1-\epsilon_{\gamma 2}) \\ \epsilon_{j1}\epsilon_{j2} & \epsilon_{j1}\epsilon_{\gamma 2} & \epsilon_{\gamma 1}\epsilon_{j2} & \epsilon_{\gamma 1}\epsilon_{\gamma 2} \end{pmatrix}$$

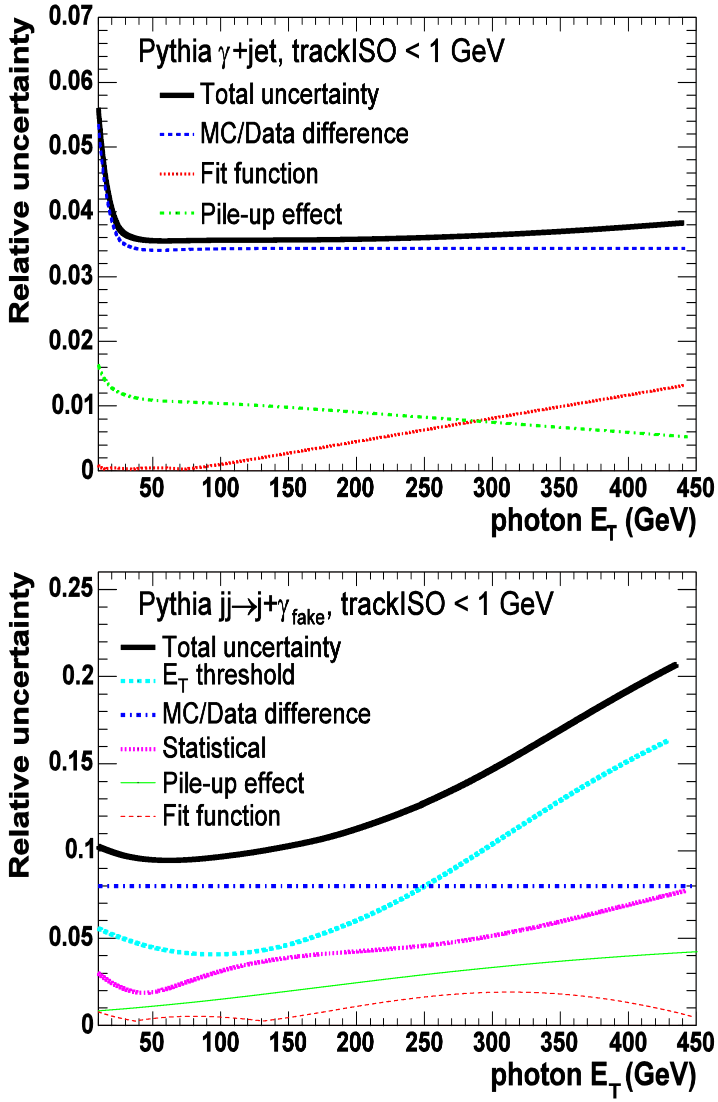
- For instance, if leading passes/trailing fails, the event weight is:

$$\begin{pmatrix} w_{ff} \\ w_{fp} \\ w_{pf} \\ w_{pp} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

- Estimated number of prompt diphoton events bin-by-bin is given by the sum of γγ weights:

$$\boxed{N_{\gamma\gamma} = \sum_{i=1}^{N_{data}} w_{\gamma\gamma}^{i}}$$

Background subtraction: 4×4 matrix method



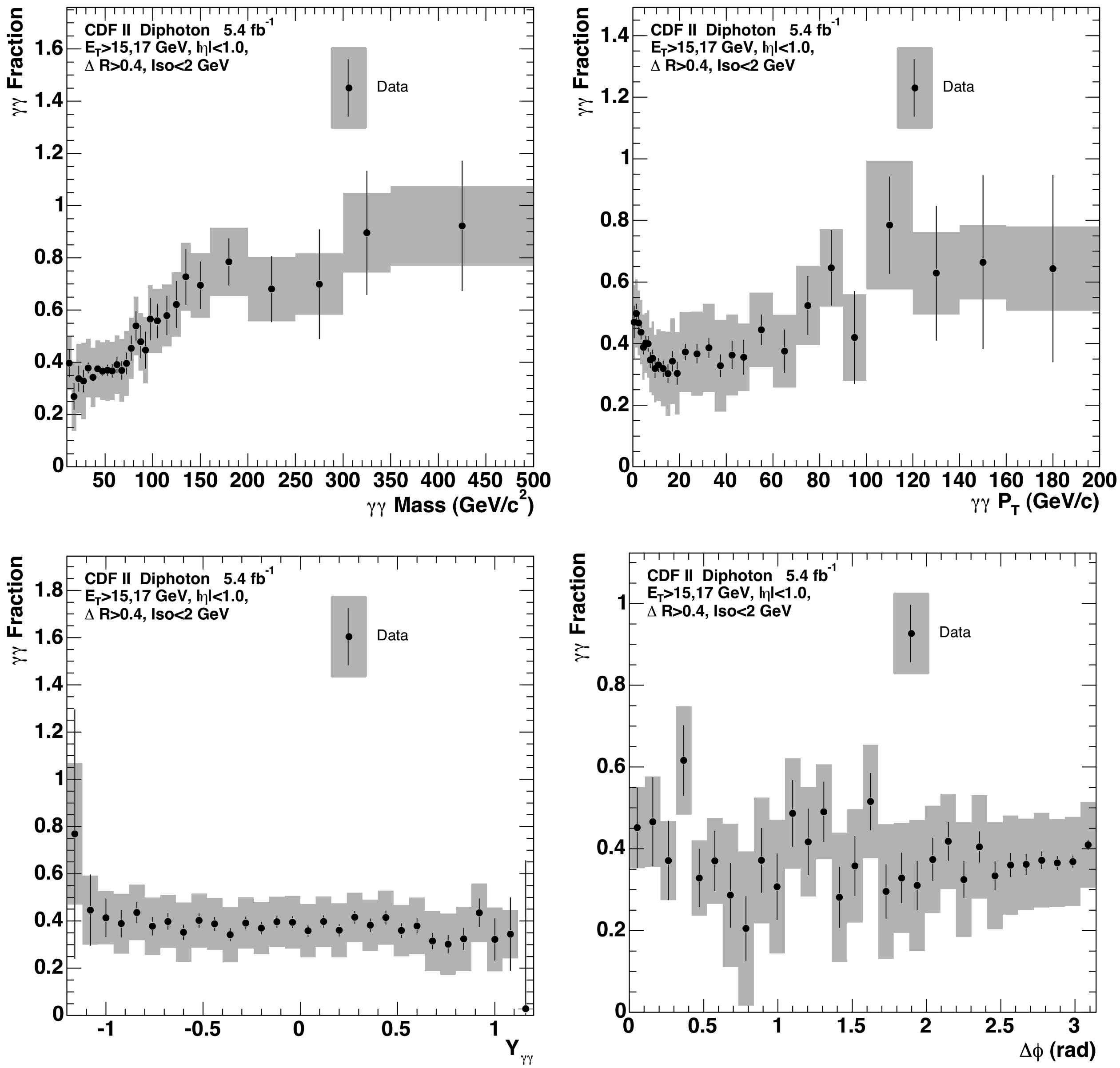
Systematic uncertainties:

- $\Delta\varepsilon_s = \pm 3.5\%$
- $\Delta\varepsilon_b = \pm 6\%$ for $E_T < 150$ GeV

➔ Leading sources of systematic uncertainty in the cross section

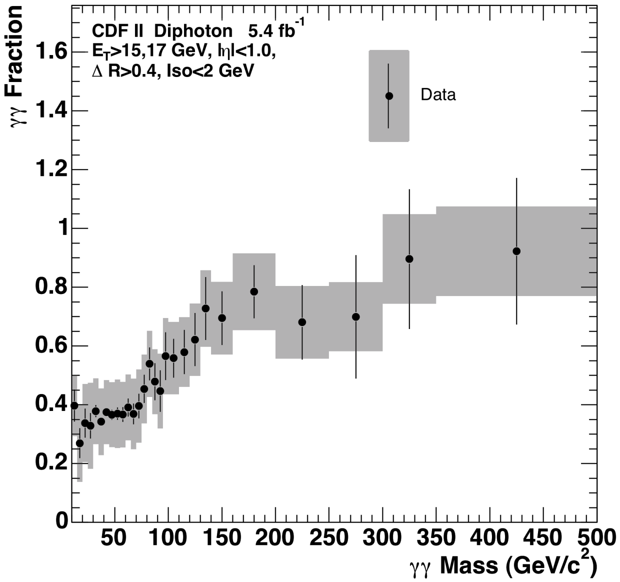
Signal fraction

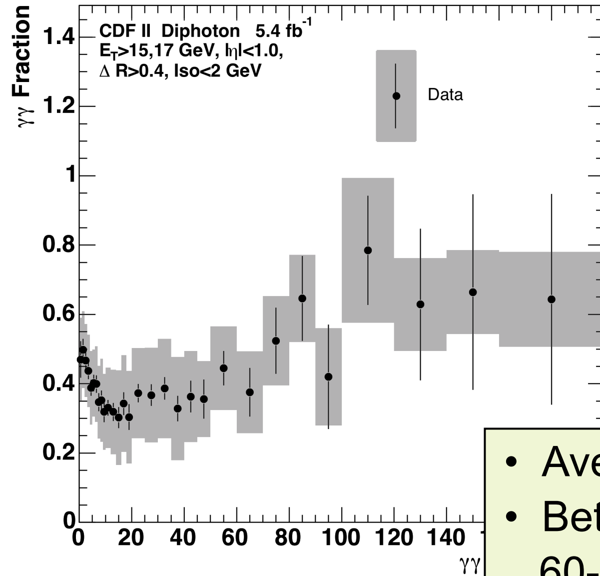
$$Signal\ fraction = \frac{N_{\gamma\gamma}}{N_{data}}$$

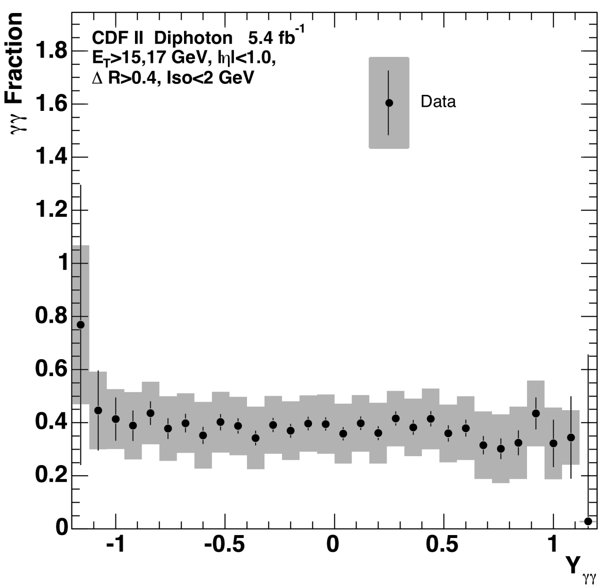


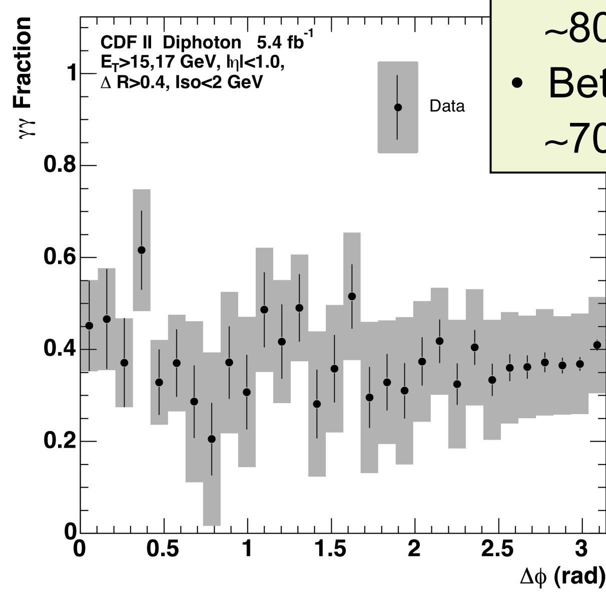
Signal fraction

$$Signal\ fraction = \frac{N_{\gamma\gamma}}{N_{data}}$$









- Average ~40%
- Better at high mass:
  60-80% for M(γγ) ~80-150 GeV/c^2
  ~80% for M(γγ)>150 GeV/c^2
- Better at high P_T(γγ):
  ~70% for p_T(γγ) >100 GeV/c

Acceptance × efficiency

$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

- Defined as:

$$\frac{\textit{Number of events with two reconstructed EM clusters passing all cuts}}{\textit{Number of events with two generator-level photons passing kinematic and isolation cuts}}$$

- Estimated using detector- and trigger-simulated and reconstructed PYTHIA events
- Procedure iterated to match PYTHIA to the data
- Corrected to parton level for comparison with NLO theory

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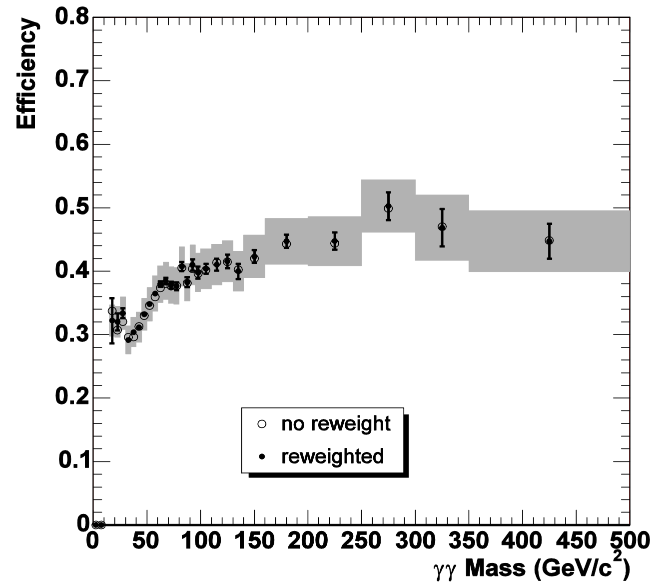
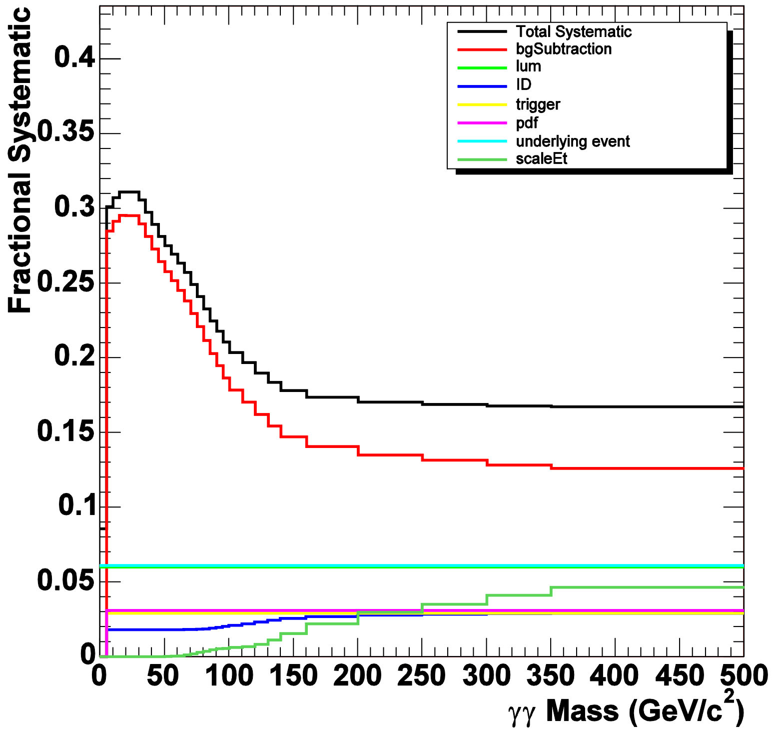


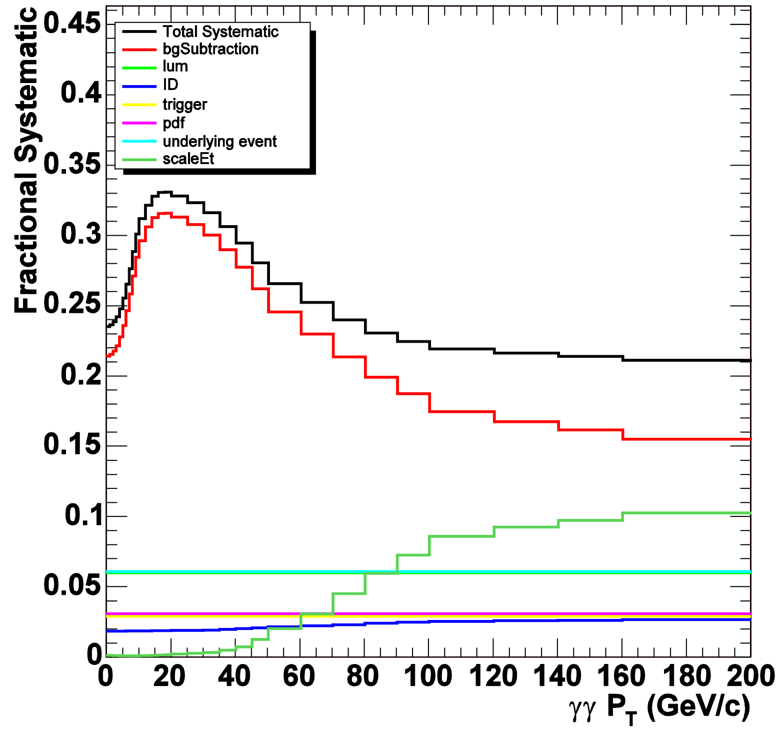
Uncertainties in the efficiency estimation:

- 3% from material uncertainty
- 1.5% from the EM energy scale
- 3% from trigger efficiency uncertainty
- 6% (3% per photon) from underlying event (UE) correction

Average efficiency ~40%
Total systematic uncertainty: ~7-15%
Comparable statistical uncertainty

Experimental systematic uncertainties





- Total systematic uncertainty ~15-30%, smoothly varying with the kinematic variables considered
- Main source is background subtraction, followed by overall normalization (efficiencies: 7%; integrated luminosity: 6%; UE correction: 6%)

Theoretical predictions

- **DIPHOX**: Fixed-order NLO calculation including non-perturbative fragmentation [T. Binoth *et al*., Phys. Rev. D **63**,114016 (2001)]

- **RESBOS**: Low-P_T analytically resummed calculation matched to high-P_T NLO [T. Balazs *et al*., Phys. Rev. D **76**, 013008 (2007)]

- **PYTHIA** 6.2.16 LO parton-shower calculation (no k-factor applied) [T.Sjöstrand *et al*., Comp. Phys. Comm. **135**, 238 (2001)]

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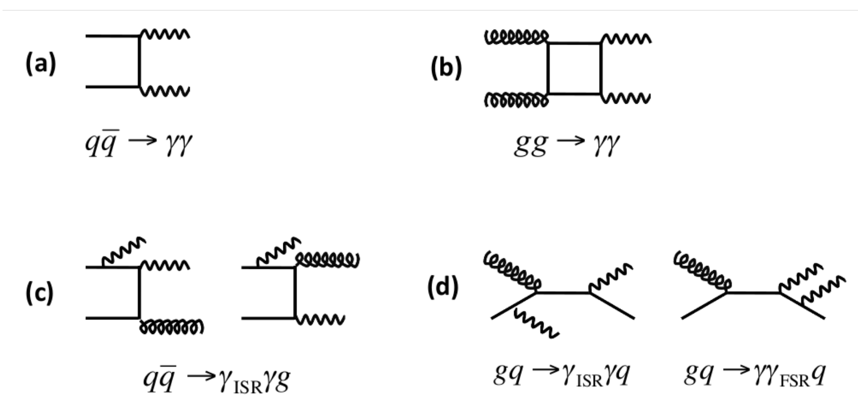

NEW calculation!

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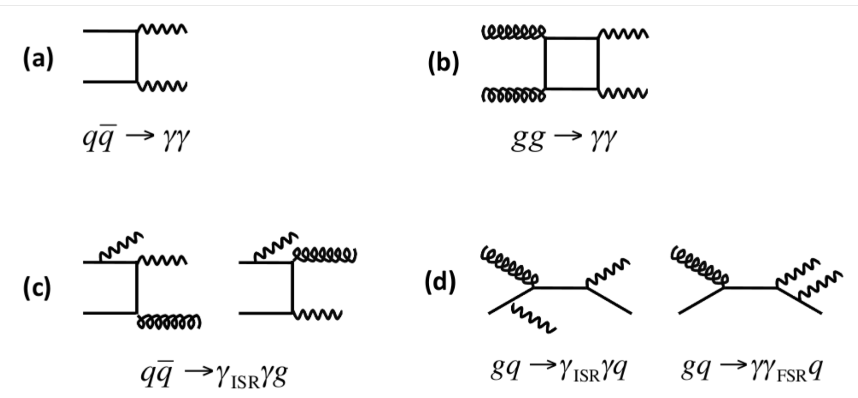
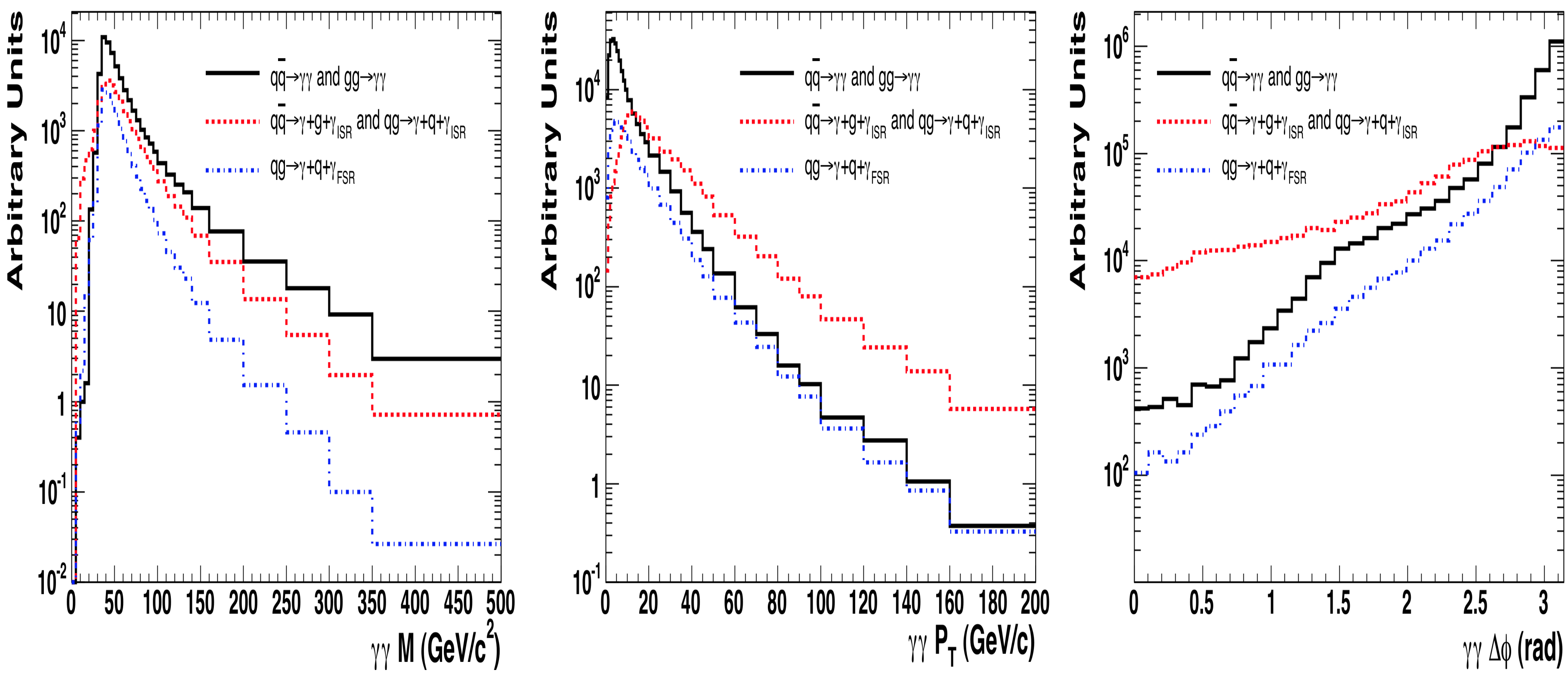


Contributions from double radiation in dijet events were examined and found small (~3% of the total) ➔ not included in this analysis

Matrix element and radiation contributions in PYTHIA



Initial state radiation (ISR) makes the $P_T(\gamma\gamma)$ and $\Delta\phi(\gamma,\gamma)$ spectra of PYTHIA harder

Theoretical predictions

- Experimental kinematic and isolation cuts are also applied to all theoretical calculations compared with the data:

  - Central photons required: $|y| < 1.1$
  - $E_T \geq 17$ GeV (1^{st} γ in the event), 15 GeV (2^{nd} γ)
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV

Imply that $\Delta R(\gamma,\gamma) \geq 0.4$

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➔ can only approximate the experimental isolation

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- NLO theoretical uncertainties:
  - PDFs: 3-6%; use 44 eigenvectors from CTEQ6.1M
  - Renormalization/factorization/fragmentation scales: ~10-20% depending on the observable; all scales simultaneously varied by ×2 up and down

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  - Isolated in t GeV

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	Total cross section (pb)
Data	$12.5 \pm 0.2_{stat} \pm 3.7_{syst}$
RESBOS	$11.3 \pm 2.4_{syst}$
DIPHOX	$10.6 \pm 0.6_{syst}$
PYTHIA $\gamma\gamma$+γj	9.2
PYTHIA $\gamma\gamma$	5.0

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Kinematic variables

$$M = \sqrt{\left(p^{\mu}_{\gamma 1} + p^{\mu}_{\gamma 2}\right)^2}$$

$$P_{\mathrm{T}} = \left| \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) - \left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}} \right|$$

$$\Delta\phi = \left|\phi_{\gamma 1} - \phi_{\gamma 2}\right| \bmod \pi$$

$$Y_{\gamma\gamma} = \tanh^{-1} \frac{\left(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2}\right) \cdot \hat{\mathrm{z}}}{\left|\vec{p}_{\gamma 1}\right| + \left|\vec{p}_{\gamma 1}\right|}$$

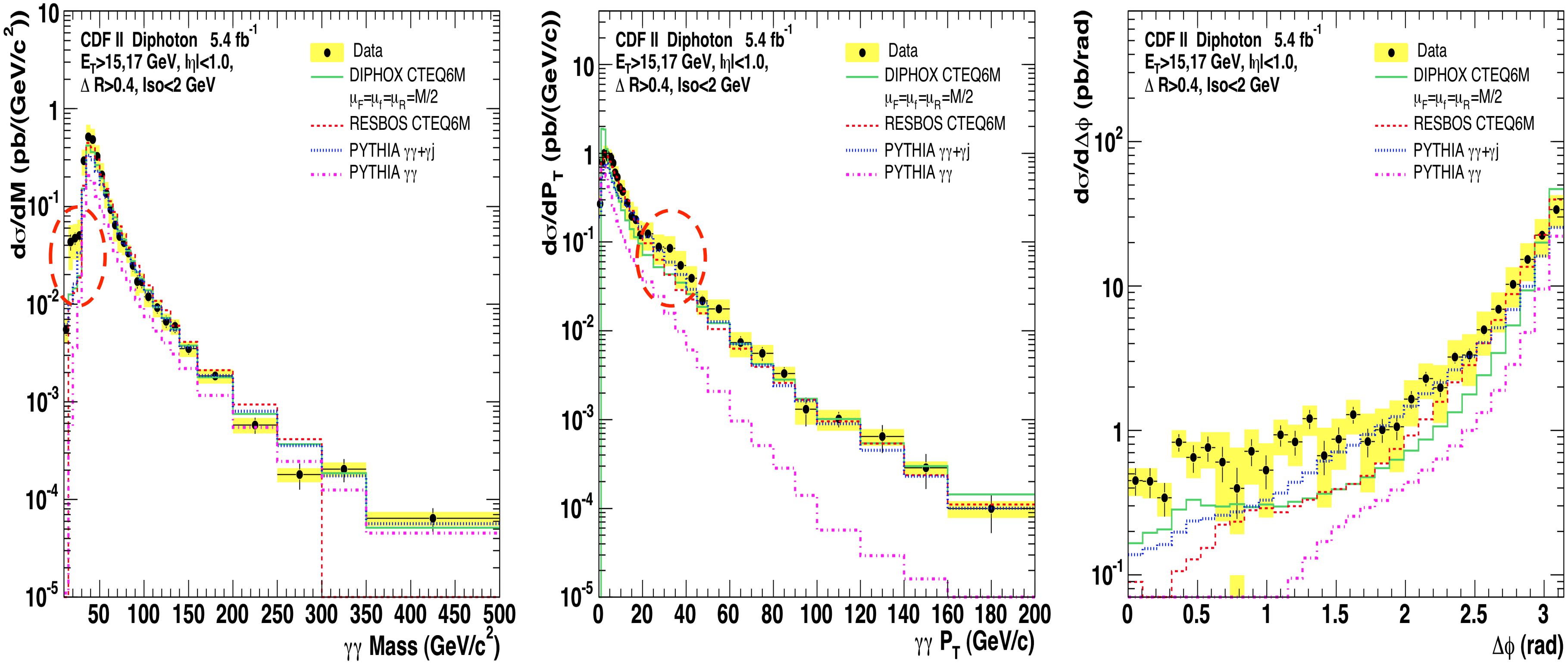
$$z = \frac{p^{<}_{\mathrm{T}\gamma}}{p^{>}_{\mathrm{T}\gamma 2}}$$

$$\cos\theta = \frac{2 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2} \sinh\left(y_{\gamma 1} - y_{\gamma 2}\right)}{M\sqrt{M^2 + P_{\mathrm{T}}^2}}
\quad
\begin{cases}
\cos\theta \rightarrow \tanh \dfrac{y_{\gamma 1} - y_{\gamma 2}}{2} \approx 0 \quad \left(P_{\mathrm{T}} << M\right) \\[2ex]
\cos^2\theta \rightarrow \dfrac{4 p_{\mathrm{T}\gamma 1} p_{\mathrm{T}\gamma 2}}{\left(p_{\mathrm{T}\gamma 1} + p_{\mathrm{T}\gamma 2}\right)^2} \approx 1 \quad \left(P_{\mathrm{T}} >> M\right)
\end{cases}$$

Cosine of the leading photon polar angle in the **Collins-Soper frame** (γγ rest frame with the polar axis bisecting the angle between the colliding hadrons)

Differential cross sections

PYTHIA γγ fails both in scale and in shape in all spectra



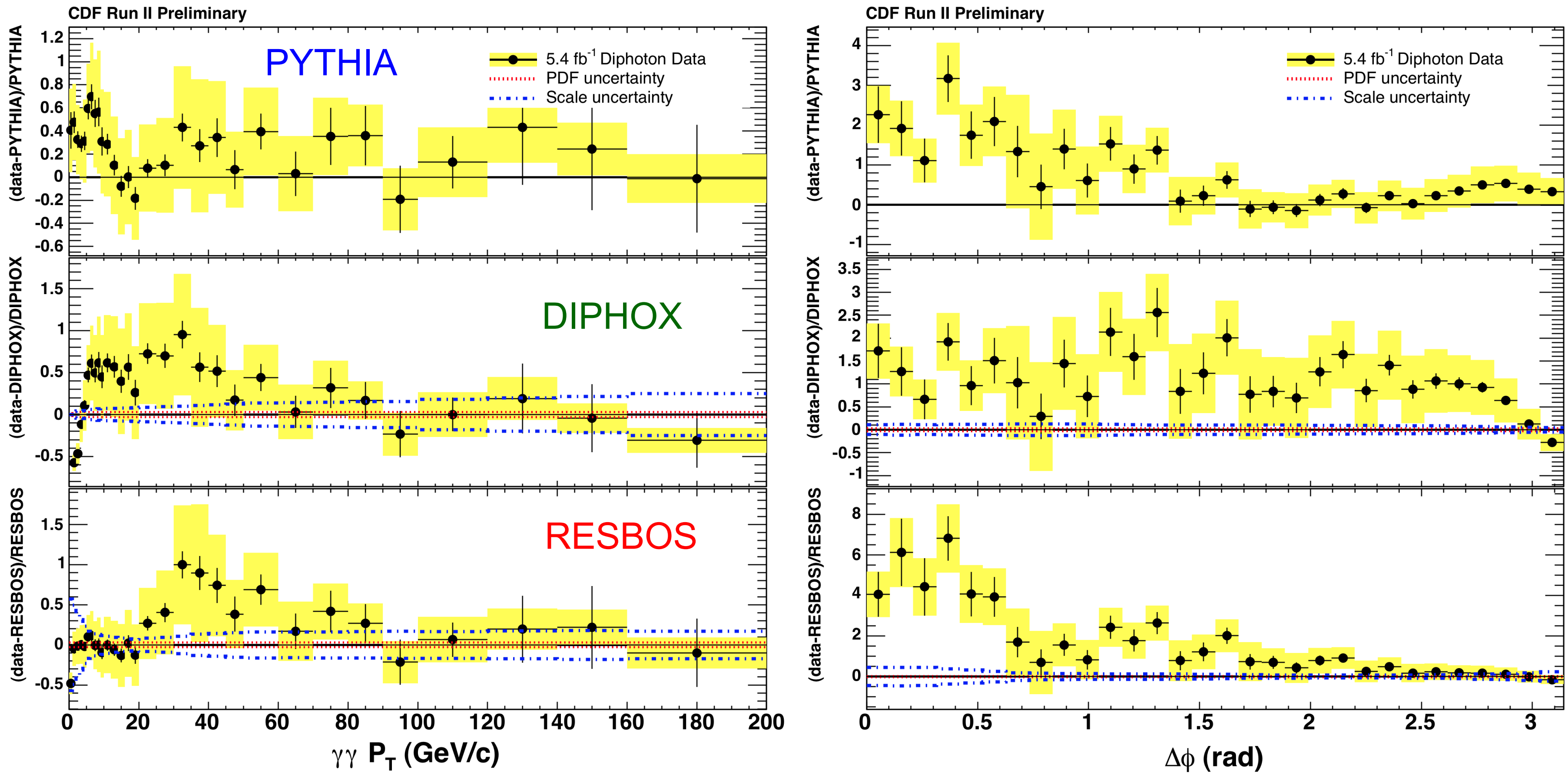
- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2

- Resummation important for $P_T(\gamma\gamma)$ > 20 GeV/c
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c (the “Guillet shoulder”)

- Resummation important for $\Delta\phi_{\gamma\gamma}$ > 2.2 rad
- Data spectrum harder than predicted

Data-to-theory cross section ratios

NB: Vertical axis scales are not the same



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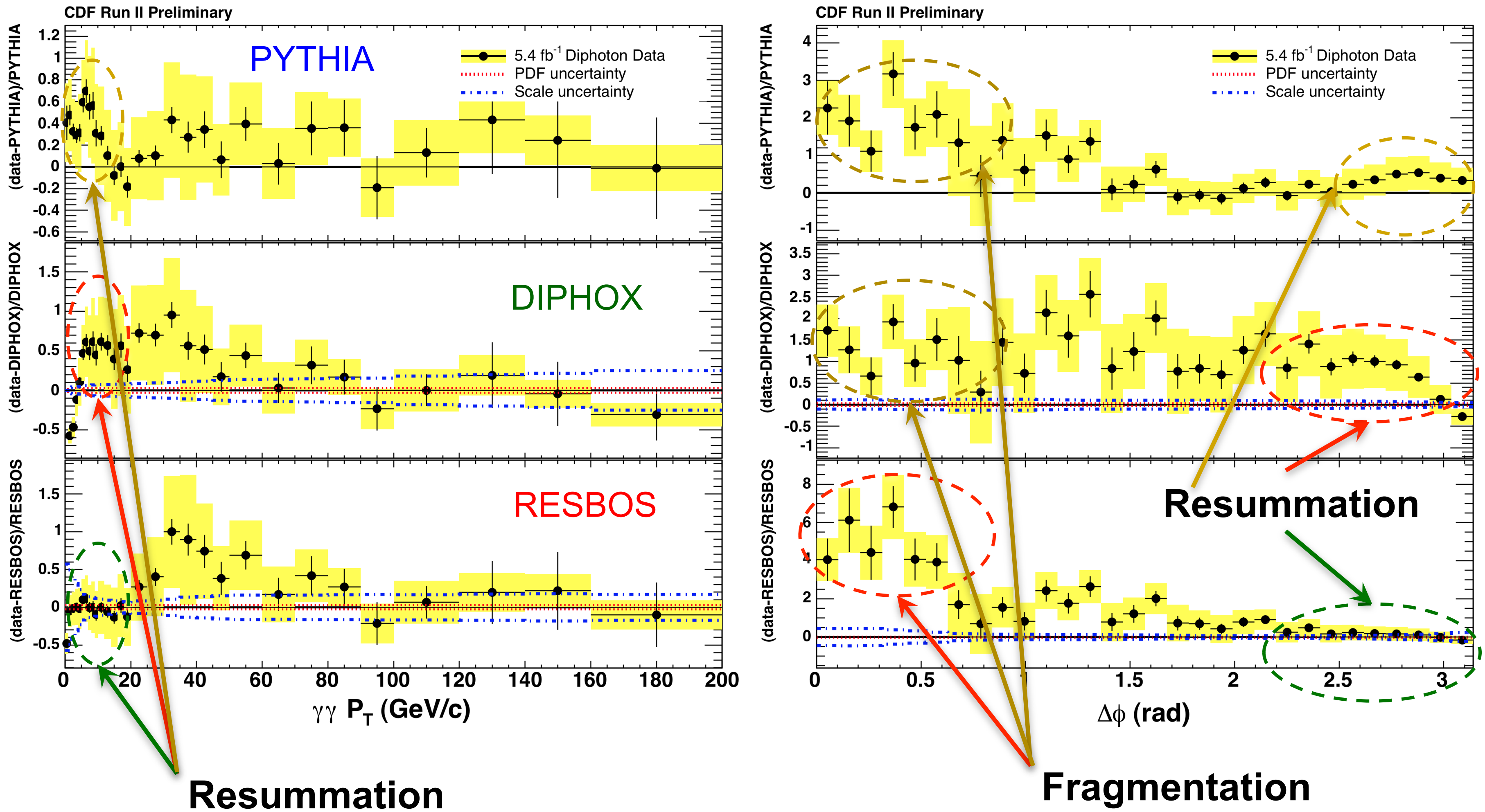
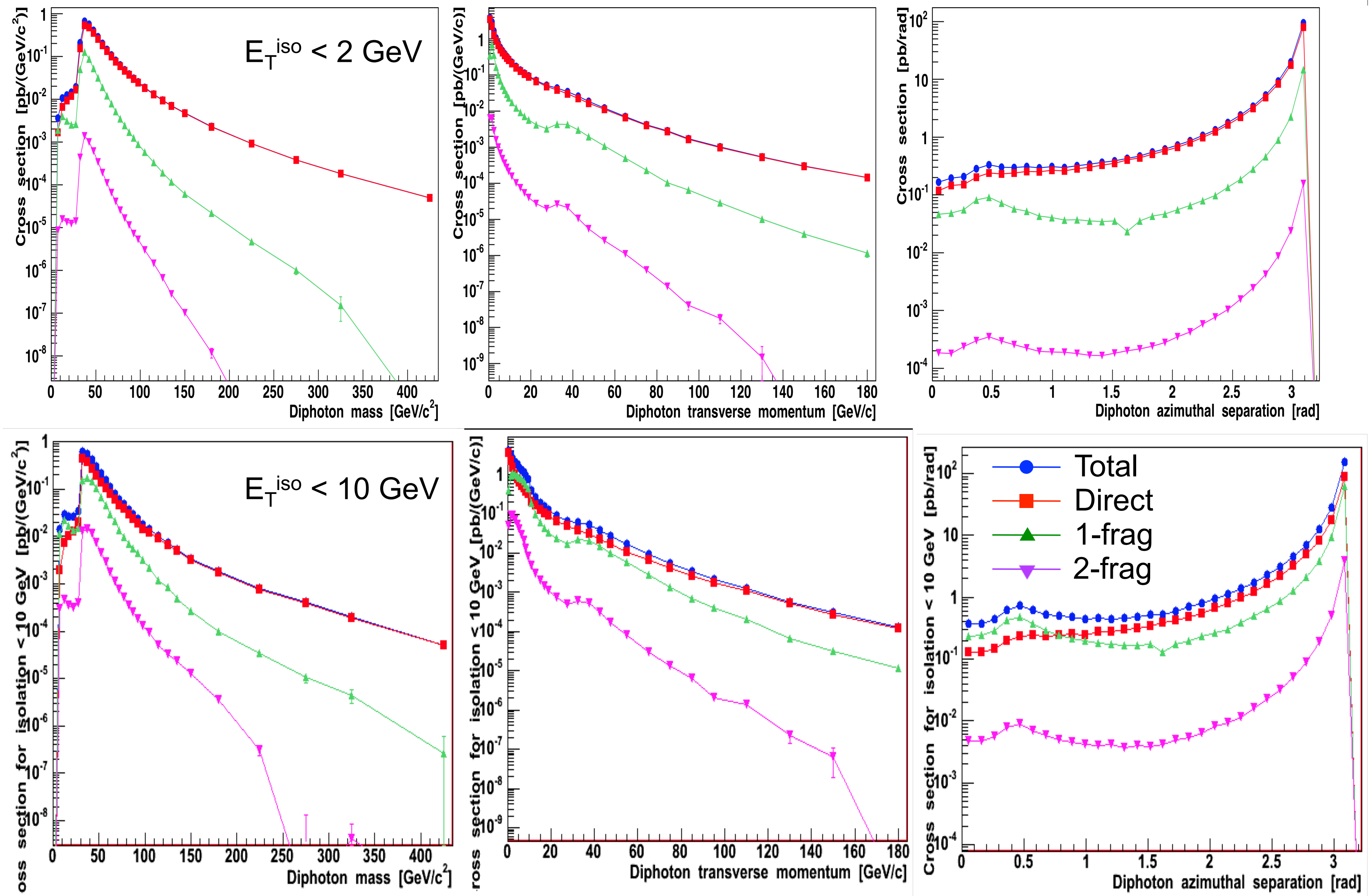


A closer look at fragmentation: DIPHOX isolation study



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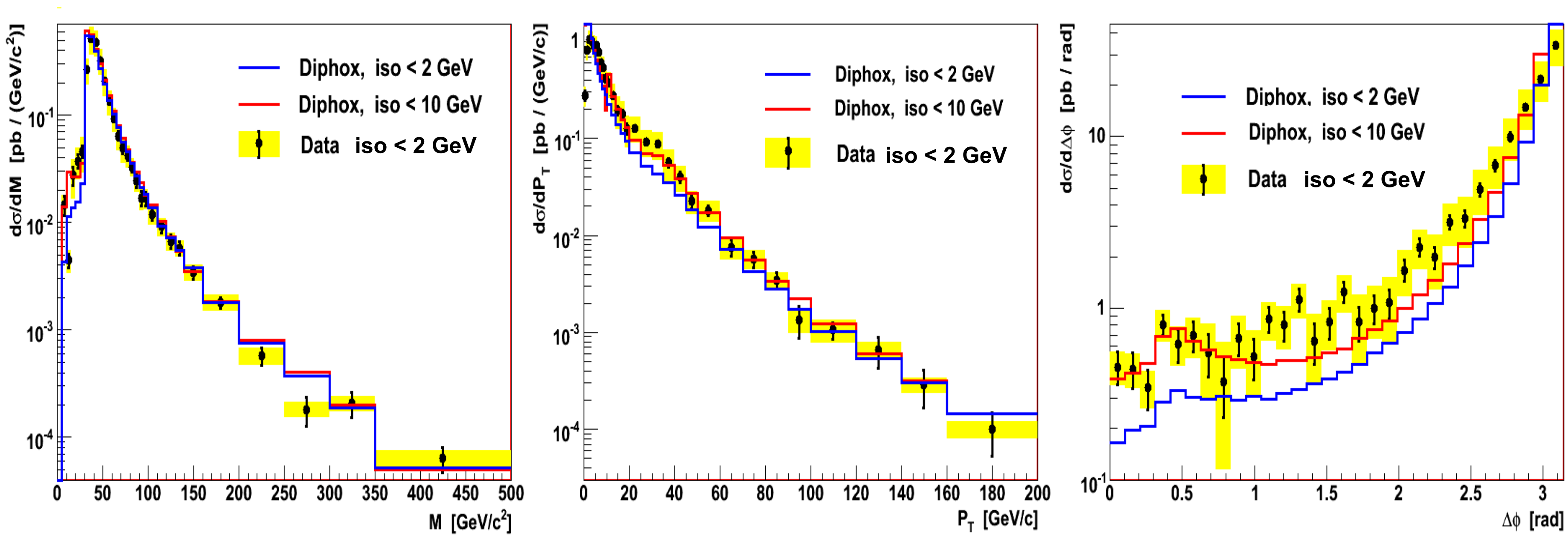
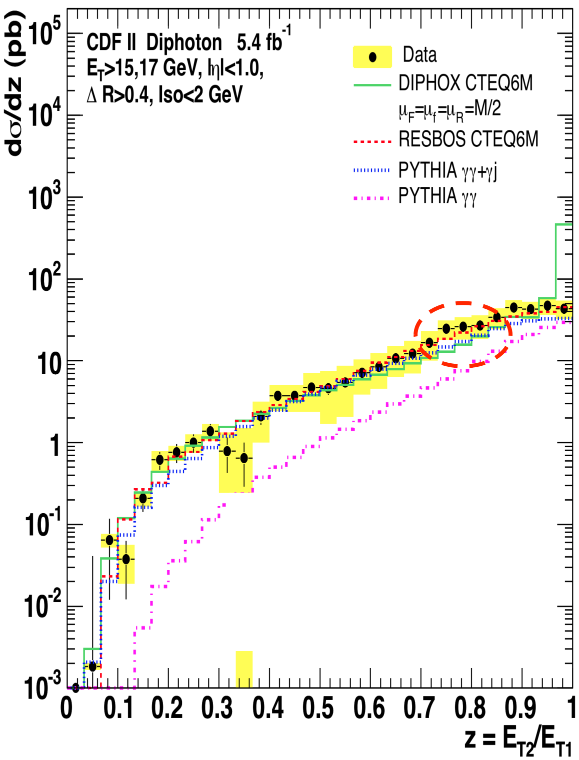
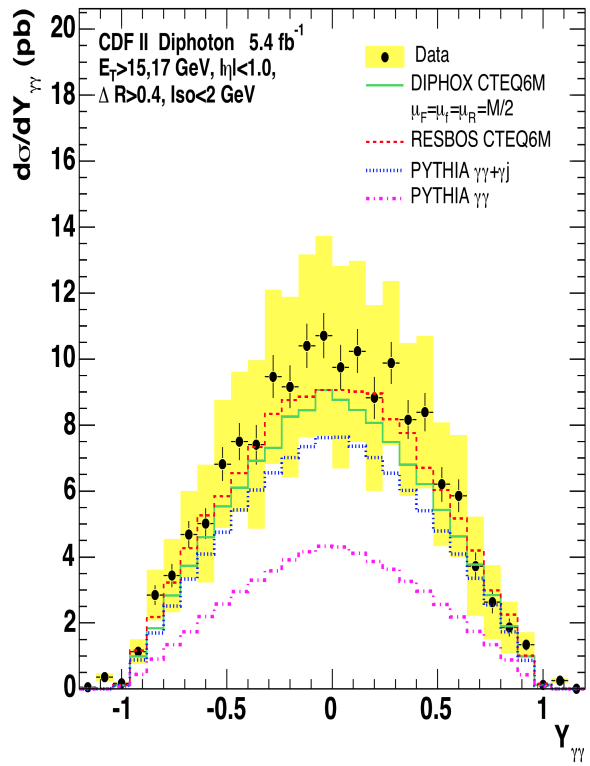
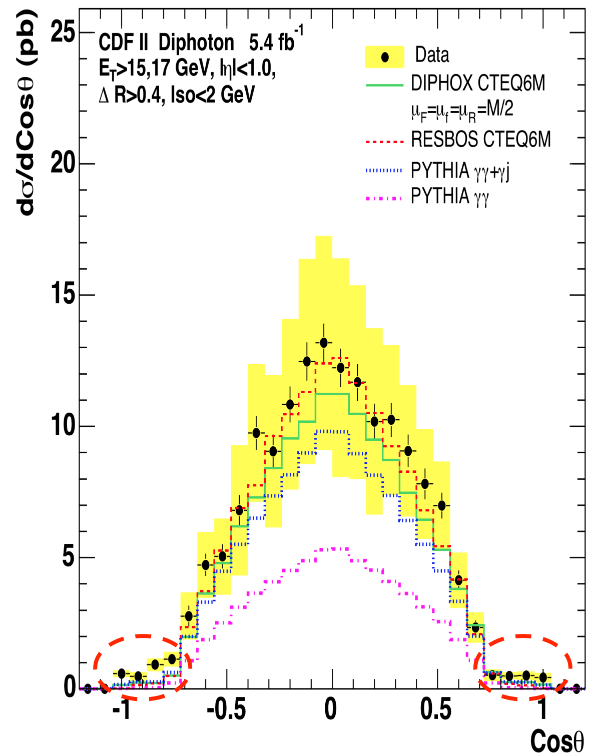


Fragmentation strength is missing from the DIPHOX calculation possibly because of the approximate application of the isolation requirement at the parton level

Differential cross sections







- Good agreement between data and RESBOS
- Good agreement between data and DIPHOX, except for $0.7<z<0.8$

- Good agreement between data and theory

- Good agreement between data and theory, except for $|\cos\theta^*|\rightarrow 1$

Data-to-theory cross section ratios

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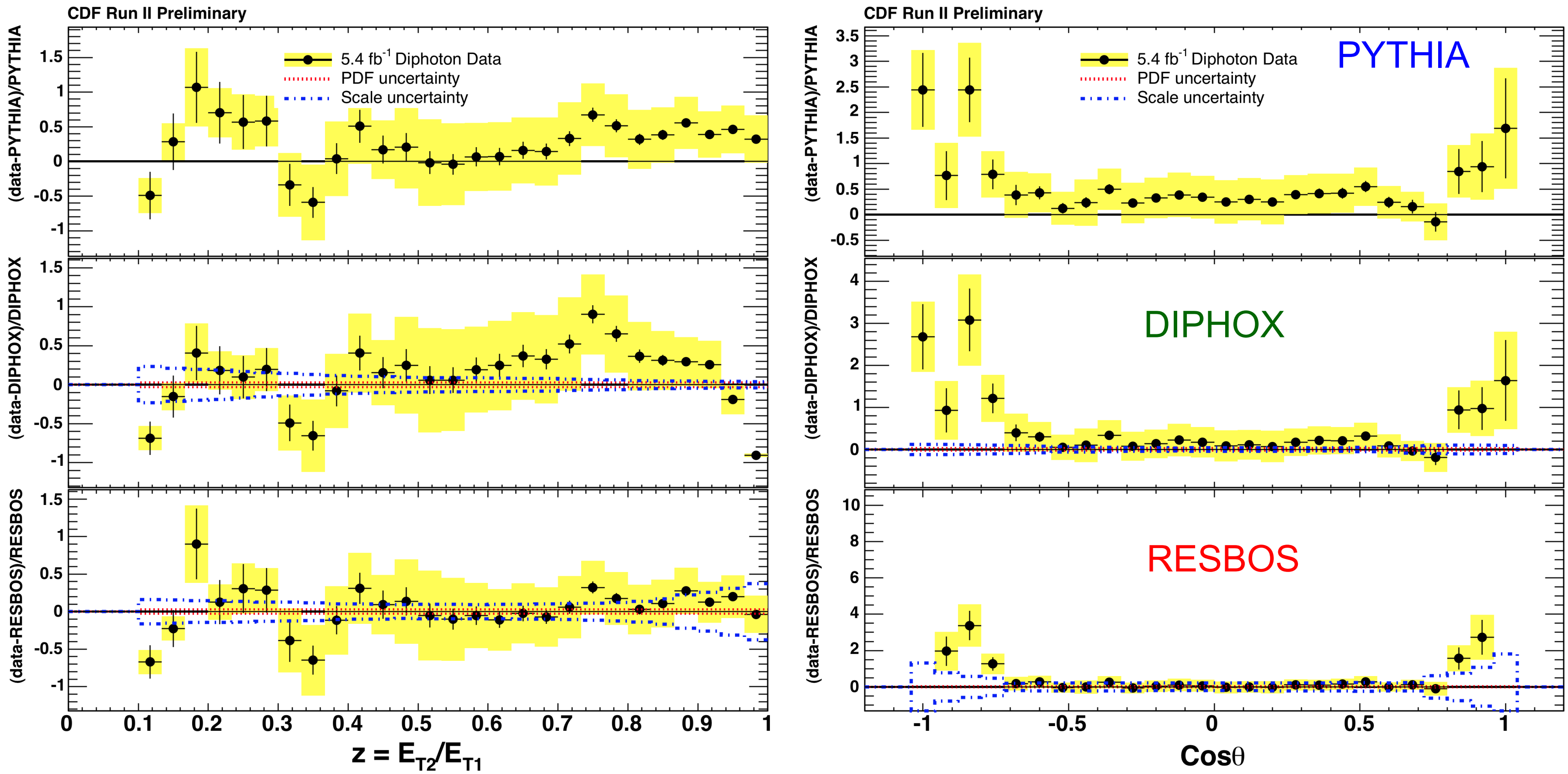

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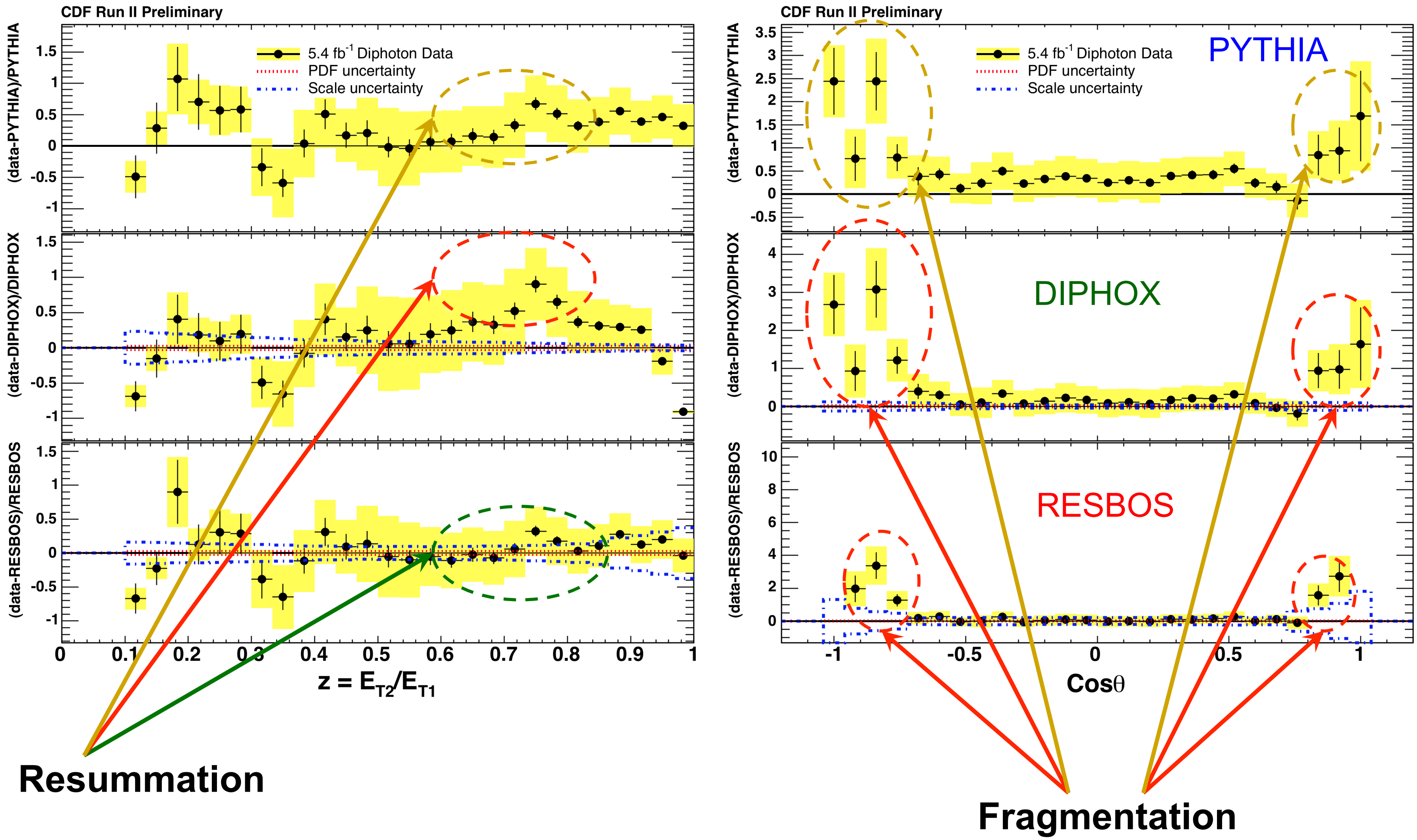
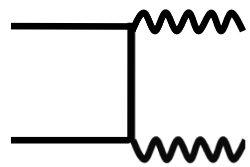
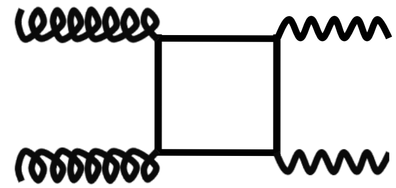


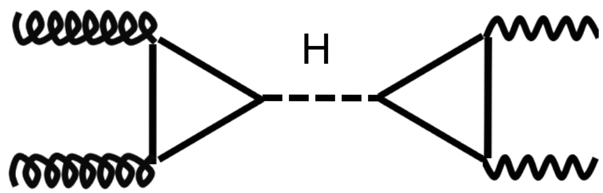
Differential cross sections for $P_T(\gamma\gamma)<M(\gamma\gamma)$

- Dominated by direct production with low P_T from gluon ISR

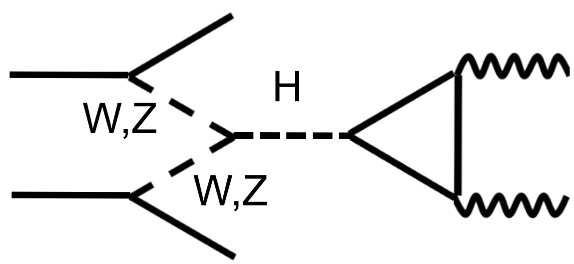


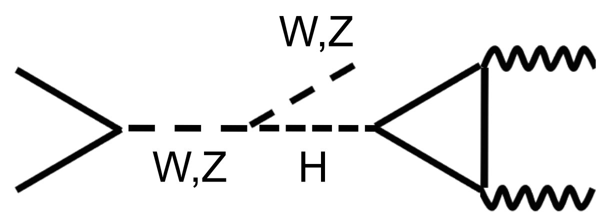


- Case kinematically similar to a Higgs boson produced by gluon fusion



- But a Higgs boson from vector boson fusion or vector boson associated production may have large P_T





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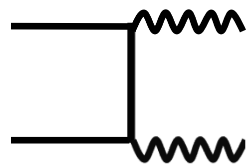

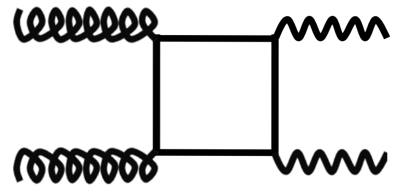

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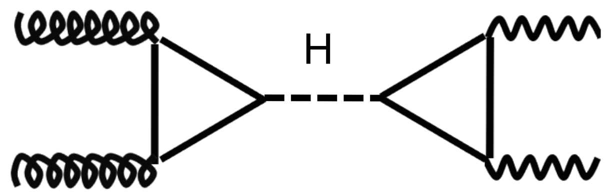

Cut only ~1.5% of ggH events @ m_H = 115 GeV/c^2

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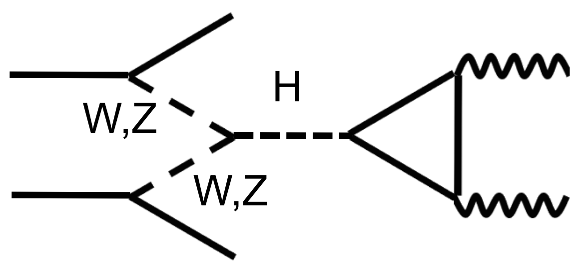
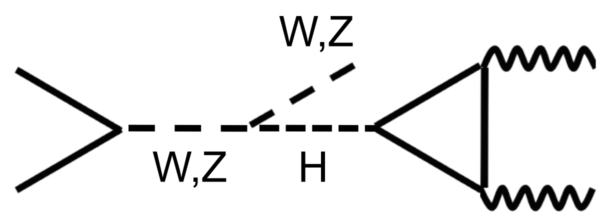
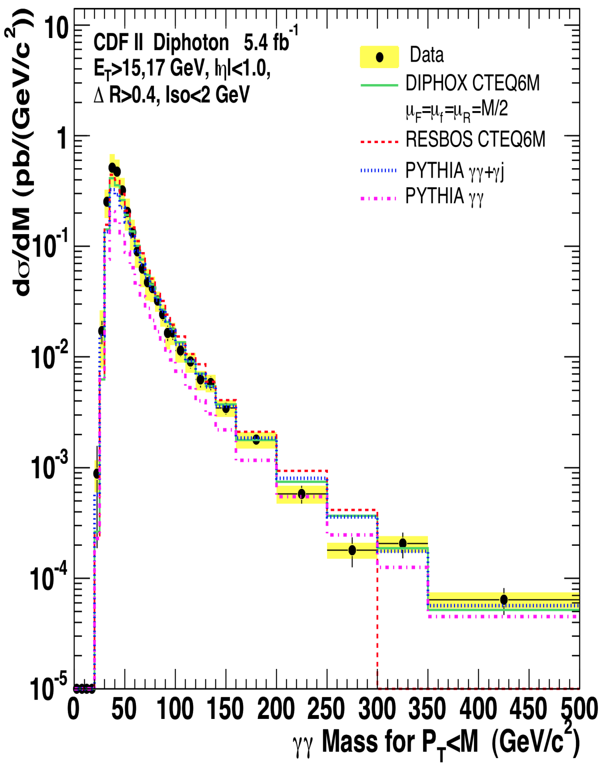
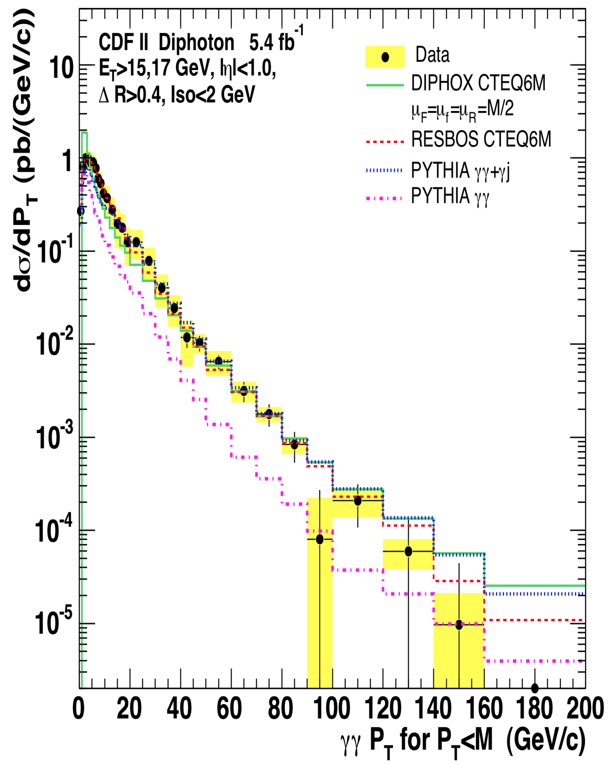


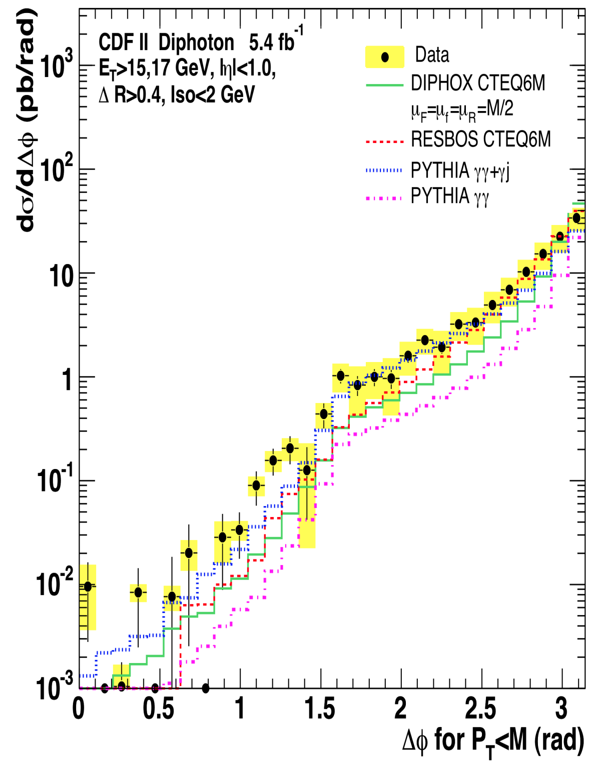


Cut ~20% of the VH+VBF events, i.e. ~6% of the signal @ m_H = 115 GeV/c^2

Differential cross sections for $P_T(\gamma\gamma)<M(\gamma\gamma)$



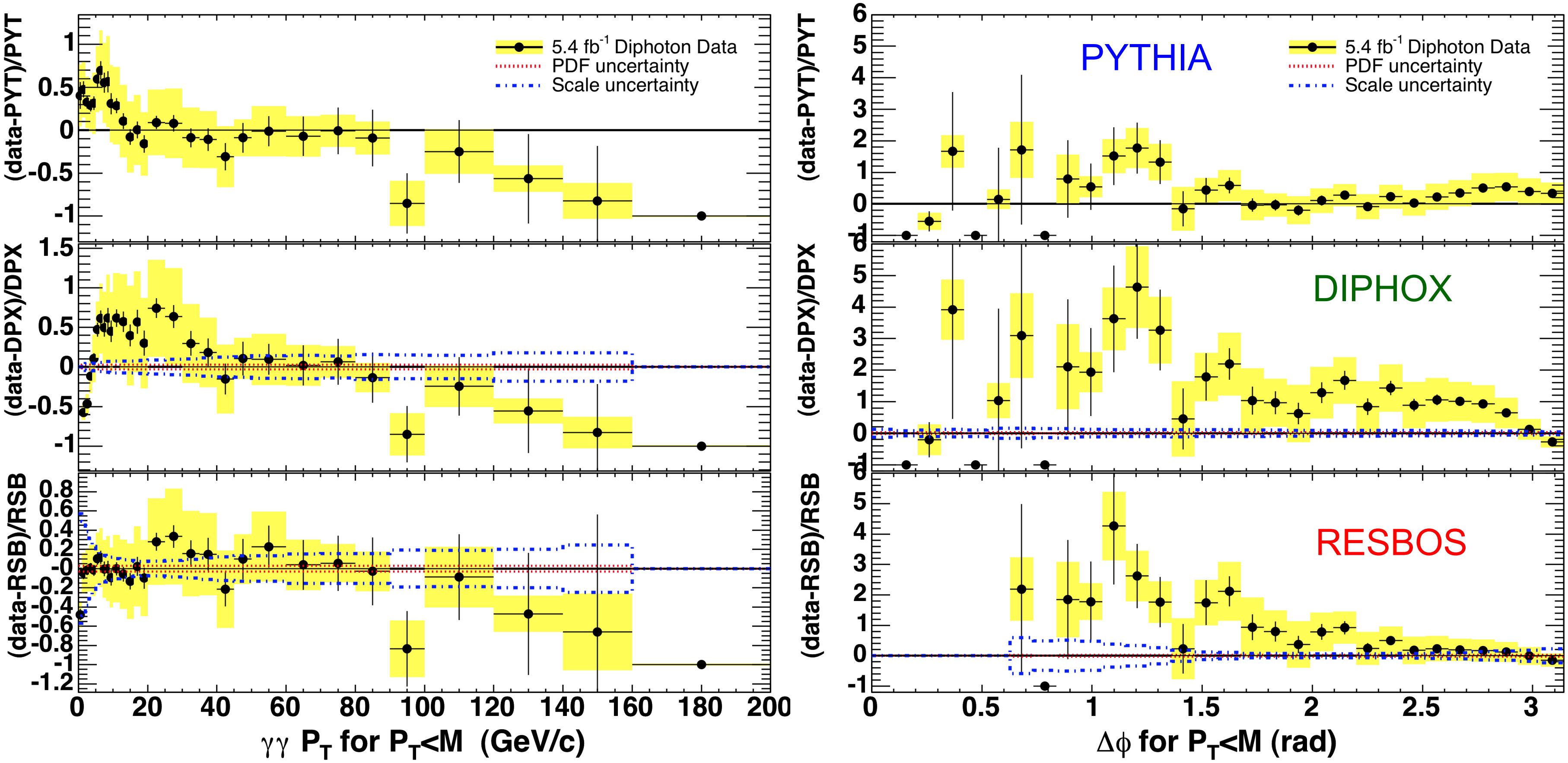




- Good agreement between data and theory
- "Shoulder" in data for $P_T(\gamma\gamma)$ = 20 – 50 GeV/c signifcantly reduced
- Discrepancies between data and theory for $\Delta\phi_{\gamma\gamma}$ < 1.7 rad reduced

Data-to-theory cross section ratios for $P_T(\gamma\gamma)<M(\gamma\gamma)$

NB: Vertical axis scales are not the same



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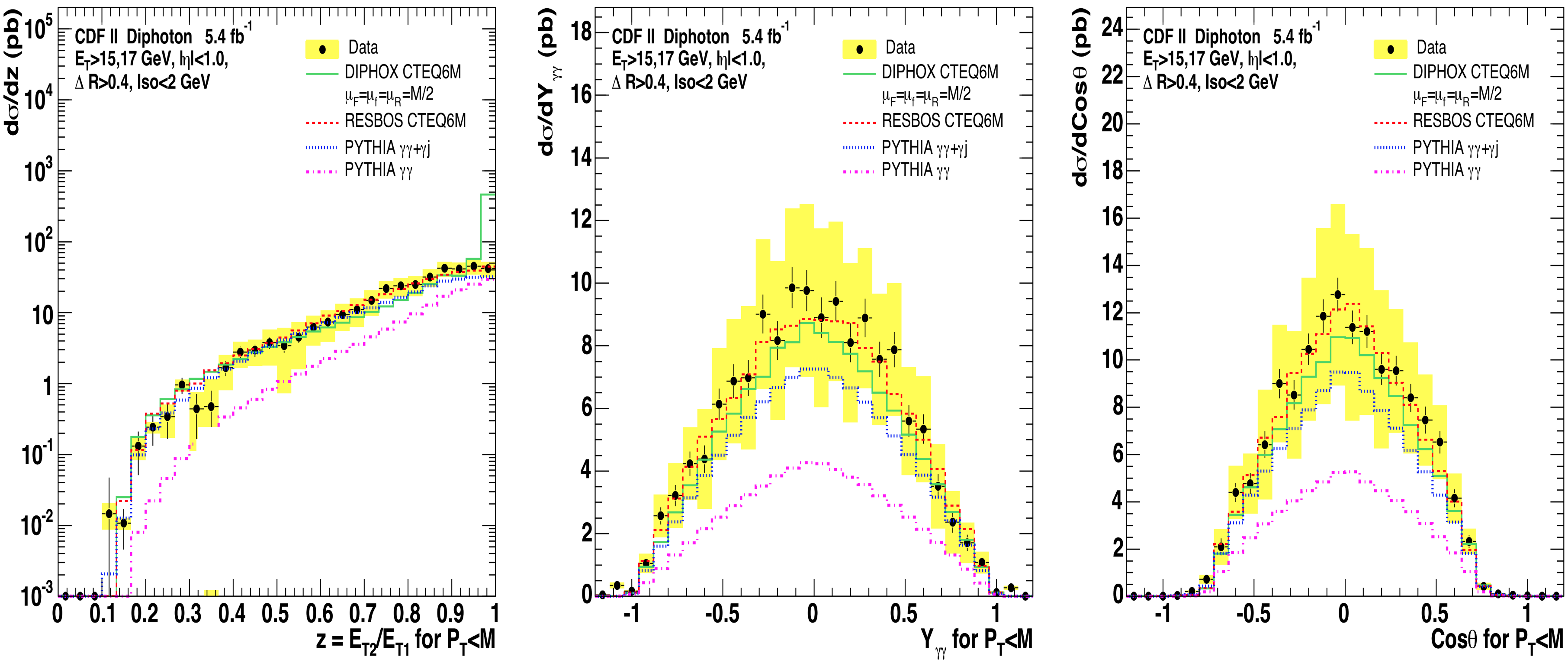

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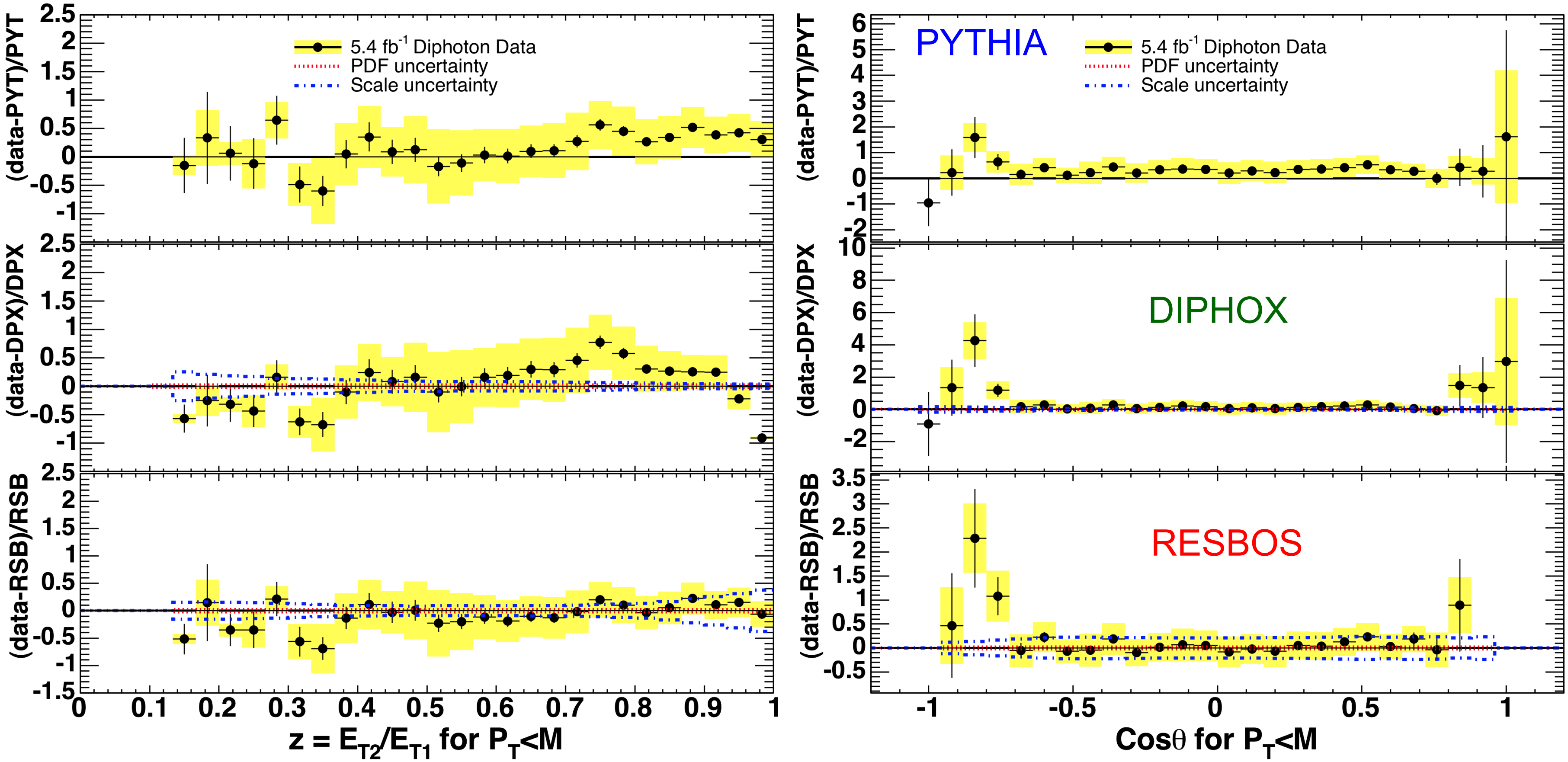
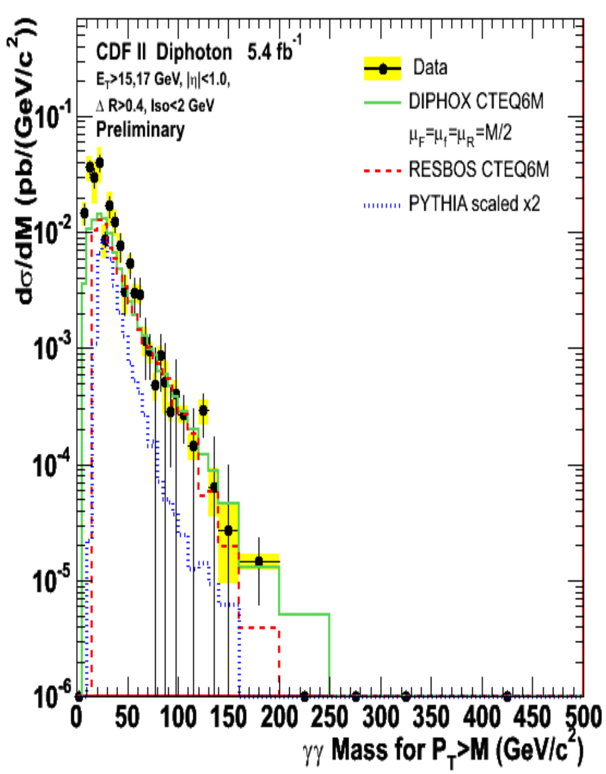


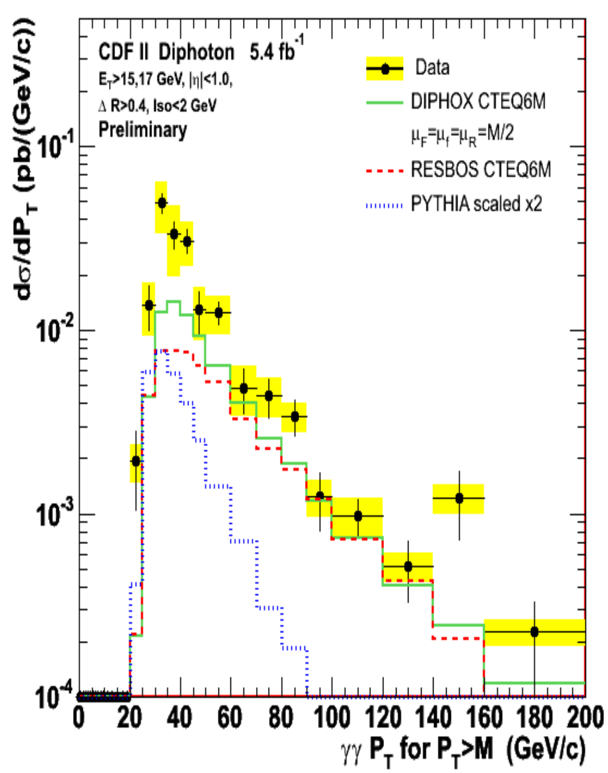
Differential cross sections for $P_T(\gamma\gamma)>M(\gamma\gamma)$

This case involves strong contributions from Compton-like scattering and fragmentations producing photon pairs with small $\Delta R(\gamma,\gamma)$

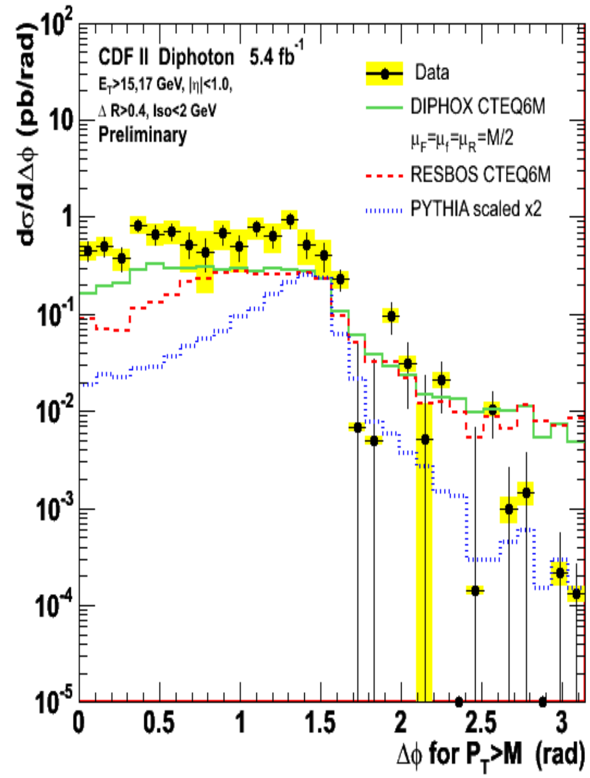
Differential cross sections for $P_T(\gamma\gamma)>M(\gamma\gamma)$



- Theory underestimates the data at the peak $M_{\gamma\gamma} \sim 30$ GeV/c^2

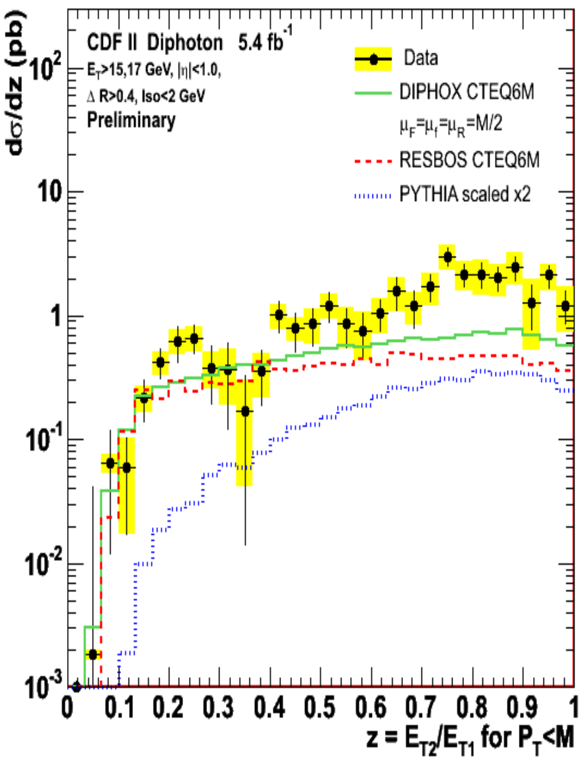


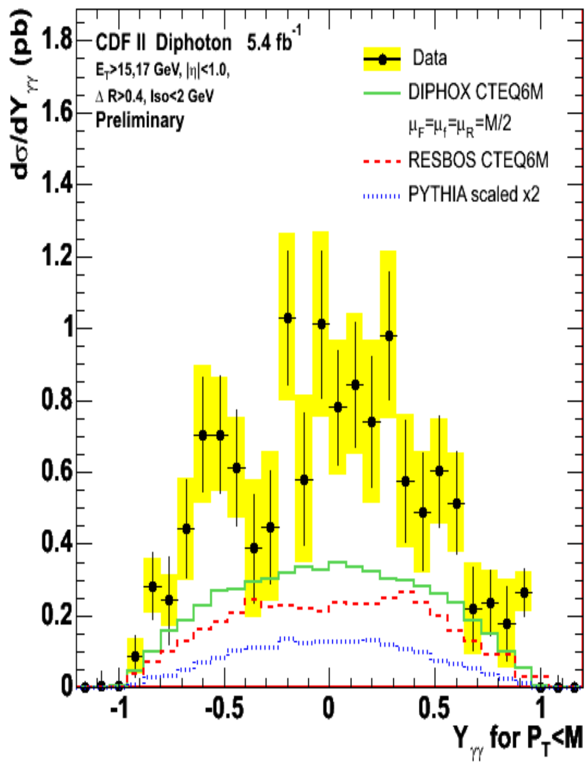
- Theory underestimates the data for $P_T(\gamma\gamma) < 90$ GeV/c

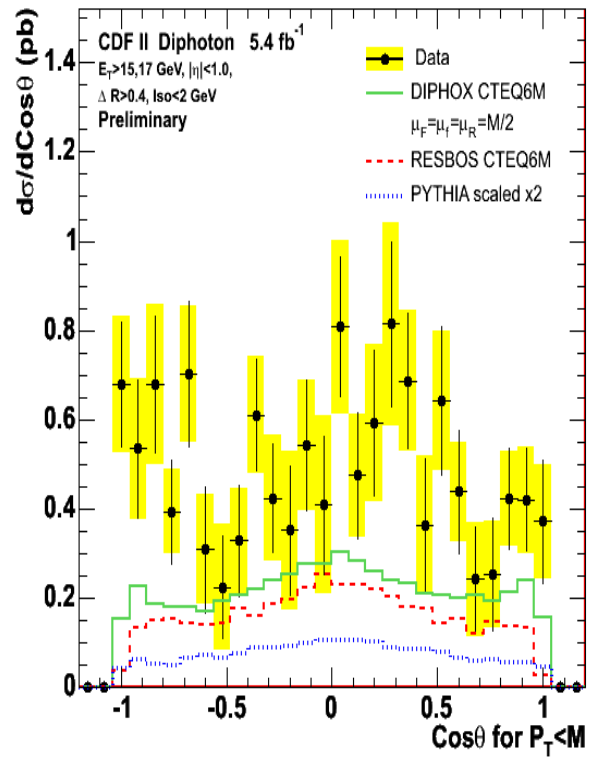


- Theory underestimates the data for $\Delta\phi_{\gamma\gamma} < 1.7$ rad

Differential cross sections for $P_T(\gamma\gamma)>M(\gamma\gamma)$







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Summary and conclusions

- **This is the most complete measurement of prompt diphoton production cross sections conducted so far** — see PRL [**107**, 102003 (2011); arXiv:1106.5123] and PRD [**D 84**, **5**, 052006 (2011); arXiv:1106.5131] references.

- The measurements are compared to state-of-the-art theoretical predictions such as **DIPHOX**, **RESBOS**, and **PYTHIA**. Overall agreement between data and theory, within known limitations, is observed.

- Resummation matched with NLO pQCD calculations works well at low $P_T(\gamma\gamma)$ (< 20 GeV/c) and large $\Delta\phi_{\gamma\gamma}$ (> 2.2 rad).

- Fragmentation appears to be not under good control in sensitive kinematic regions [$M(\gamma\gamma)$ < 60 GeV/c^2, 20 GeV/c < $P_T(\gamma\gamma)$ < 50 GeV/c, $\Delta\phi_{\gamma\gamma}$ < 1 rad].

- The poor theoretical description of data regions sensitive to fragmentation raises a caveat: More sophisticated isolation methods are required to further reduce fragmentation contributions

- Parton-shower Monte Carlo provides a description of the data competitive with full NLO calculations by including ISR and FSR photons, which add some NLO features to the calculation as well as an approximation of fragmentation.

Impact on searches of undiscovered particles

- The success of parton-shower Monte Carlo is important for the search of a low-mass Higgs boson and of new physics:

  - Provides a reliable background model for these searches in the framework of realistic event representation suitable for simulation of collider experiments

  - Can be used in the Higgs $\longrightarrow$ $\gamma\gamma$ search based on a multivariate analysis that exploits the full $\gamma\gamma$ event information — all kinematic variables that can help discriminate Higgs boson decays from QCD $\gamma\gamma$ events: see D0's PRL (arXiv:1107.4587) reference

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- CDF recently measured a limit on H $\longrightarrow$ $\gamma\gamma$ using a mass scan of 7 fb^{-1} of data:

http://theory.fnal.gov/jetp/talks/FNAL_wc_Hgamgam.ppt

The sensitivity of this search can be significantly improved by updating the search using a multivariate analysis based on the PYTHIA $\gamma\gamma$+γj model of the QCD background.